HENRY ROYCE INSTITUTE

M4QN
Materials for Quantum Network

Future Directions for Materials for Quantum Technologies

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Commissioned by M4QN
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Executive summary

The importance of quantum technologies for advancing a range of different applications from computing to communications, sensing and timing has been recognised by many governments around the world. It is expected *that 'countries that develop and use quantum technologies will have advantages in terms of productivity, economic growth, health, sustainability, and national security and resilience'*[1].

The UK's National Quantum Strategy vision is '... *for the UK to be a leading quantum-enabled economy, recognising the importance of quantum technologies for the UK's prosperity and security*'[1].

The global market value for quantum technologies (QTs) is anticipated to surpass $30 billion by 2026[2] to a projected $106 billion by 2040, driven by the application of quantum computing in financial services. Material developments, specifically addressing the requirements for application within QTs, will play a fundamental role in the implementation and commercial exploitation of those technologies.

The Materials for Quantum Network (M4QN[3]) was established and funded in 2022 by the Engineering and Physical Sciences Research Council. The Network brings together the world-leading UK materials research base, the existing National Quantum Technologies Programme (NQTP), and the developing quantum technologies industry base in a UK-wide coordinated effort. M4QN has two main objectives; the formation of new interdisciplinary research communities and identification of new interdisciplinary research topics within application areas.

The Henry Royce Institute (Royce[4]) is the UK national centre for research and innovation of advanced materials. The Institute's founding partners were the universities of Manchester, Sheffield, Leeds, Liverpool, Cambridge, Oxford and Imperial College London, as well as the UK's Atomic Energy Authority and the National Nuclear Laboratory. Royce supports material research in many different areas such as 2D materials, advanced materials processing, atoms to devices, biomedical materials, chemical materials design, energy storage, material systems for demanding environments, materials for energy efficient ICT and nuclear materials.

M4QN, with the support of Royce, commissioned IfM Engage to design and deliver a roadmapping workshop with the following aims:

- Identify the **future directions for materials** that address challenges in the context of the QT areas of; Computing, Sensing and Imaging, Positioning, Navigation and Timing (PNT). The roadmap would help to inform case studies for investment by the government via the UK National Quantum Technologies Programme (UK-NQTP), UKRI and industry. The case studies should address the '**what next**' question that is needed for investment in materials-focused QT research. Specifically:

[1] https://www.gov.uk/government/publications/national-quantum-strategy
[2] https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20technology%20sees%20record%20investments%20progress%20on%20talent%20gap/quantum-technology-monitor-april-2023.pdf
[3] https://m4qn.org
[4] https://www.royce.ac.uk

- The future directions should link the capabilities and materials to science and applications and especially link materials to the UK-NQTP National Quantum Strategy goals and missions
- The future directions document can be used as a vehicle for communicating with policy holders
- The future directions document will help to inform where funding and investment is needed
- The future directions document should include developments needed for materials used to create quantum objects (e.g. qubits) as well as those required for supporting materials (e.g., glues, adhesives etc.)

A two-day workshop was conducted in January 2024 to explore the themes of **challenges** and **material developments** in the context of the three aforementioned application areas: (i) Quantum Computing and Communications; (ii) Quantum Sensing and Imaging; and (iii) Quantum Positioning, Navigation and Timing (PNT). Eighty-one (81) participants from academia, industry and government attended and contributed their ideas on priority challenges and required material developments for quantum technologies.

The **main challenges** identified across the different QTs are shown in the figure below.

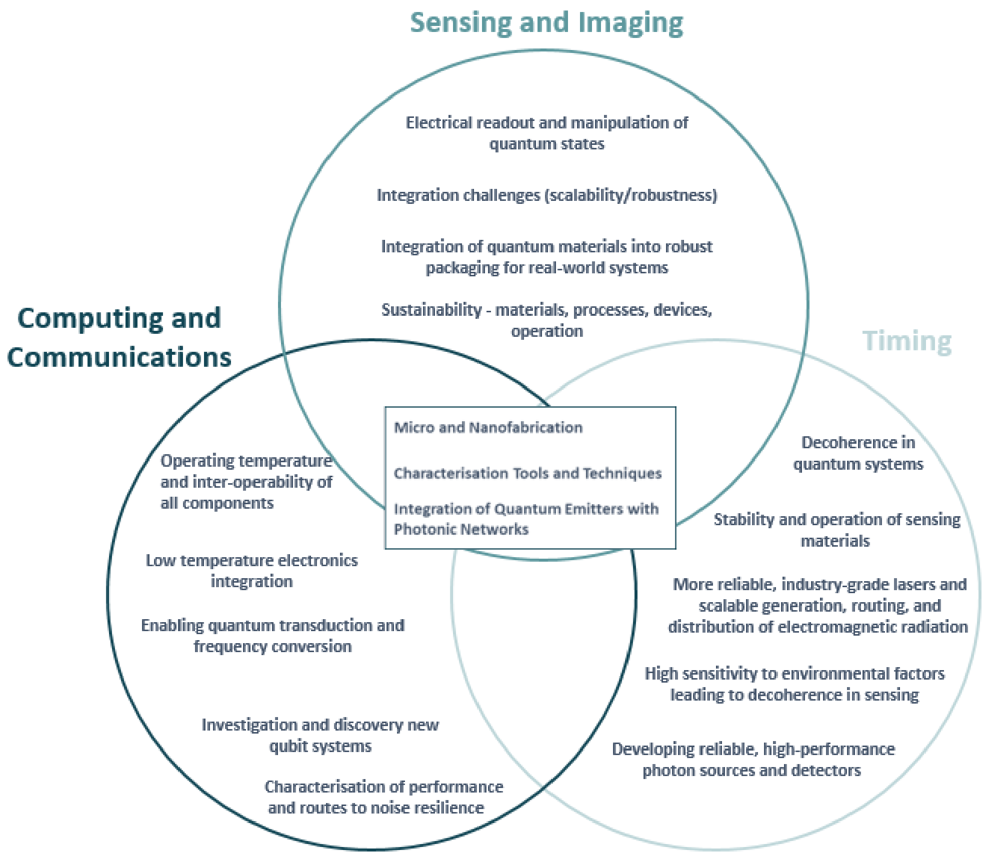

Figure 1: Venn diagram representing overlaps in key material challenges across Computing and Communications; Sensing and Imaging; and Timing applications

The main **common challenges** identified across all three technology areas were the following:

- Developing and maintaining internationally leading characterisation capability for quantum platforms and metrology, (e.g. for calibration in vivo, internal strain, environmental variables, nanoscale spectroscopic characterisation at low temperature; in-situ materials characterisation interfaces, operation under vacuum etc.)
- Micro and Nanofabrication capability delivering the spatial control of functionality and interfaces for solid state QTs (e.g., precise positioning of colour centres in diamond, control of host isotopic purity, defect/impurity control, surface quality management, and functionalisation for enhanced quantum sensing).
- Efficient integration of solid state quantum devices with photonic networks (e.g. on-chip QD based photonic sources, control of desired QD state, high brightness site control).

The **material development priorities** across the different QTs are shown in the figure below.

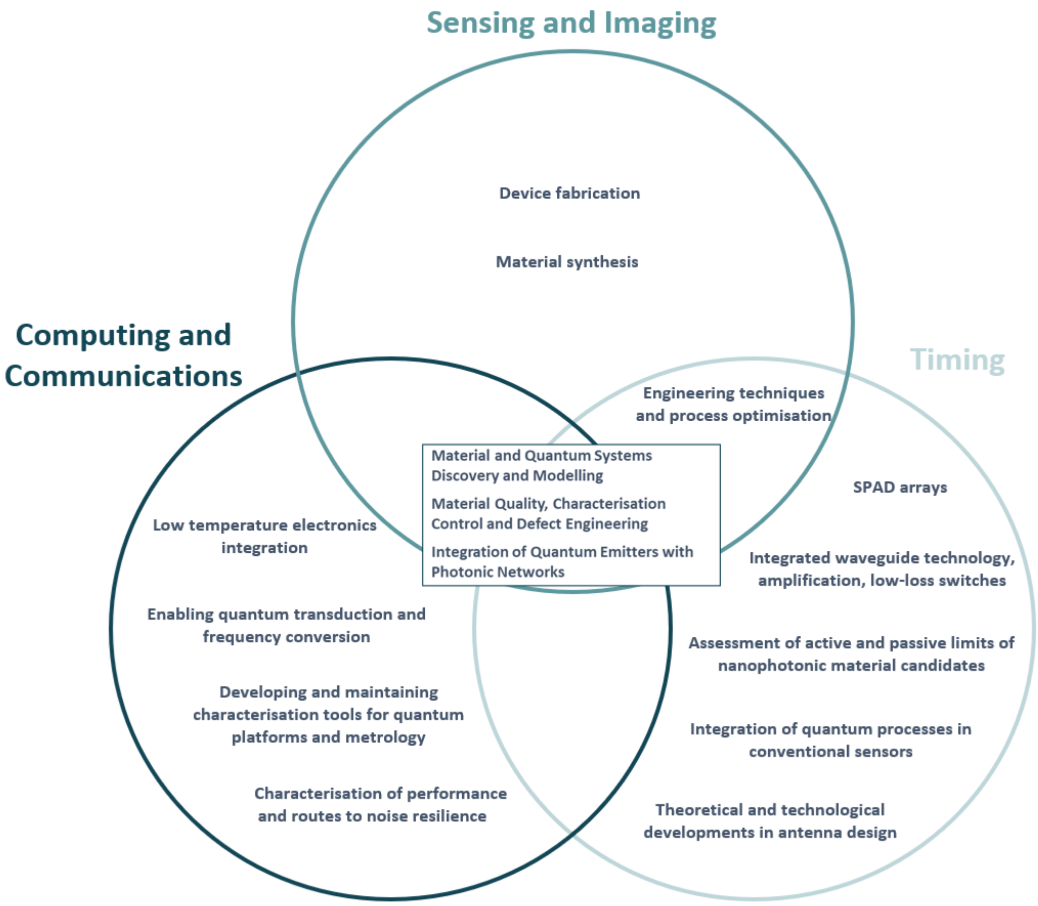

Figure 2: Venn diagram representing overlaps in key material developments across Computing and Communications; Sensing and Imaging; and Timing applications

Common topics were prioritised and selected for Computing and Communication and Sensing and Imaging. Specifically, the **common material requirements between the two technology areas** were the following:

- Materials Development and Efficient Photonic Integration of Solid State Quantum Emitters - Multifaceted material integration including heterojunctions, nanophotonic device fabrication, and precise interfacing techniques; development of materials towards on-chip photonic systems, e.g., integration of source/transmitter and receiver/detector; ultra low-loss optical materials for quantum photonic integrated circuits; developing new materials for non-linear optics in quantum photonics
- Material Quality and Characterisation Quality Control. Defect Engineering - Material Quality and characterisation quality control: quality control in defect materials e.g., SiC, Diamond, rare earth doped crystals etc.; tailoring doping, isotopic composition, purity, with resilient UK supply; material quality and characterisation including trap density management, defect control, nano-atomic characterisation, and polycrystalline structure understanding. Micro and Nanofabrication challenges of control and positioning for technologies on solid state
- Material and Quantum Systems Discovery and Modelling. Investigation and discovery of new qubit systems including 2D, topological and spintronics systems - Exploring alternative growth techniques like MBE and PEALD; research on materials with higher critical temperatures; high-quality thin film materials; automated discovery and characterisation of spin systems in different materials with optimal measurements; material discovery and formulation innovation

The **main Figures of Merit** identified across the different QTs are shown in the figure below.

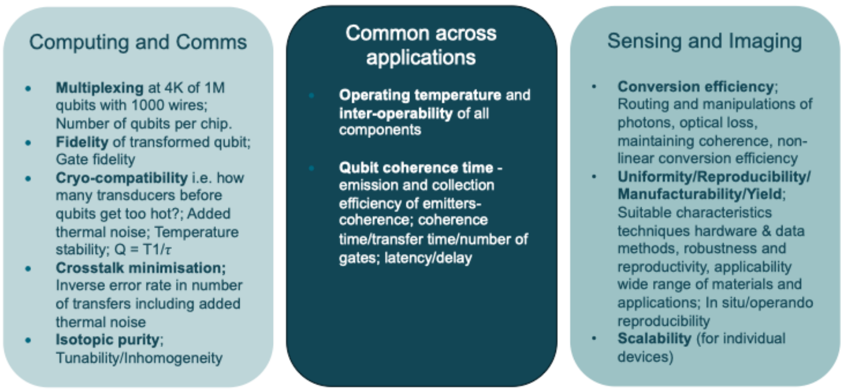

Figure 3: Figures of Merit across Computing and Communications; and Sensing and Imaging;

Two **common Figures of Merit (FoM)** were identified across the technology areas explored:

- Qubit coherence time
- Emission and collection efficiency of emitters; time/transfer, time/number of gates; latency/delay

Skills and training requirements pervade all technology areas. These include **attracting new researchers** into the field, **supporting, upskilling and/or continuing to develop existing researchers,** and **creating new educational and community programs** to train the next generation of researchers and engineers in QTs. **Encouraging innovative thinking** by **supporting proposals that are unconventional** and diverge from the mainstream narrative is also important.

Policy can play an important role by helping **co-ordinate activities at a national level** (both for skills development, and focus areas), establishing **international partnerships** and **access to fabrication facilities**, **attracting international talent** and **supporting the burgeoning UK industry**.

Infrastructure is critical to helping the UK quantum community advance in areas ranging from **modelling** and **high-performance computing** to **small-scale laboratories for 2D material synthesis and characterisation, nanofabrication facilities, large-scale infrastructure for manufacturing quantum devices**, **wafer testing pilot production facilities and open foundries** to enable industrial-scale manufacturing in the UK. A **UK facility** dedicated to **diamond material innovation**, fostering a seamless transition from high-precision development to practical, large-scale production is also needed for sensor and imaging applications.

Equipment should include a range of **imaging, spectroscopy,** and **analysis techniques** necessary for the discovery, characterisation and performance evaluation of different concepts and systems.

Some of these facilities may already exist in the UK, some need to be improved and some will need to be developed to ensure the UK continues to be in the forefront of technological innovation.

Funding is needed for the **recruitment/retention of experienced personnel**, **research projects**, and **equipment**. **Interdisciplinary collaborations** between different specialities, and **laboratory exchanges** including representatives from both industry and academia are also important for progressing in this field.

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Background

Quantum technologies

The so-called ‘first quantum revolution’ of the early 20th century laid the groundwork for quantum physics and significantly influenced modern technology and society. For instance, technology developed during this era led to the invention of lasers and transistors, essential components in the development of computers, telecommunications, satellite navigation, smartphones, and advanced medical diagnostics[5].

The second quantum revolution is now underway, involving the detection and manipulation of single quantum objects to take full advantage of quantum physics concepts to advance and develop new technologies.

Quantum technologies leverage the properties of quantum effects – the interactions of molecules, atoms, and particles smaller than atoms to develop practical applications across various fields. New capabilities are anticipated in a range of technology domains, including Computing and Communications; Sensing and Imaging; and Positioning, Navigation and Timing (PNT).

The global market value for quantum technologies (QTs) is expected to surpass $30 billion by 2026[2] with some estimates for the potential QT market reaching up to $106 billion by 2040, an increase driven by the application of quantum computing in financial services[3]. The success and implementation of these technologies will fundamentally depend on the development, application, and use of various materials.

Materials for quantum technologies

Quantum materials, with their exotic physical properties rooted in quantum mechanics[6], include a range of solids like superconductors, heavy fermions, multiferroics, and newer discoveries such as topological quantum matter, two-dimensional materials, and their van der Waals heterostructures, Moiré materials, Floquet time crystals, and materials and devices for quantum computation with Majorana fermions[7].

These materials promise revolutionary advancements but are only a subset of the broader spectrum of materials essential for the development of mature, reliable, and cost-effective quantum technologies. The majority of the needs at the heart of quantum systems will be met by more conventional materials like complex oxides, ferroelectrics, nonlinear optical, 2D materials, engineered impurities in semiconductors, insulating materials, molecular materials, glasses and magnetic alloys, all underpinned by theory and simulation, characterisation and processing.

The exploration and development of materials for quantum applications present significant scientific and technological challenges and opportunities. The Quantum Staging Group (QSG) ran a “Challenges in Advancing Our Understanding of Atomic-Like Quantum Systems: Theory and Experiment” workshop to discuss key near-term challenges that need to be addressed to further

[5] https://ec.europa.eu/commission/presscorner/detail/de/MEMO_18_6241
[6] https://www.osti.gov/servlets/purl/1616509
[7] https://iopscience.iop.org/article/10.1088/2515-7639/abb74e/meta

promote and accelerate development of solid-state atom-like systems with applications in quantum technologies[8]. While this workshop was focused on the group's selection of solid-state systems, a broader high-level overview is required to fully capture the opportunities and challenges across the spectrum of materials for quantum applications. To stay at the forefront of innovation comprehensive support mechanisms must be developed and deployed, including specialised skills training programmes, the establishment of forward-thinking policies, the construction of suitable infrastructure, and the provision of funding to fuel ongoing research and development.

Materials for Quantum Network (M4QN)

In June 2022 the Engineering and Physical Sciences Research Council announced funding to establish the **Materials for Quantum Network (M4QN)**. The Network brings together the world-leading UK materials research base, the existing National Quantum Technologies Programme (NQTP), and the developing quantum technologies industry base in a UK-wide coordinated effort.

M4QN has two primary objectives[2]:

1. The formation of new interdisciplinary research communities that:
    a. bring together researchers in materials and quantum technologies;
    b. spans academia and supports engagement with start-ups and industry via the NQTP;
    c. facilitates communication and collaboration through common language;
    d. supports the development of a new generation of 'Quantum Smart' researchers;
    e. promotes diversity and inclusivity at every level.
2. The identification of new interdisciplinary research topics within application areas that:
    a. address current needs of those developing quantum technologies for near-term and future deployment;
    b. demonstrate the evidence base for future investment;
    c. secure the UK's momentum and international leadership in quantum technologies.

In March 2023 the UK government published the **National Quantum Strategy**[1], comprising five (5) overarching missions:

- Mission 1: By 2035, there will be accessible, UK-based quantum computers capable of running 1 trillion operations and supporting applications that provide benefits well in excess of classical supercomputers across key sectors of the economy.
- Mission 2: By 2035, the UK will have deployed the world's most advanced quantum network at scale, pioneering the future quantum internet.
- Mission 3: By 2030, every NHS Trust will benefit from quantum sensing-enabled solutions, helping those with chronic illness live healthier, longer lives through early diagnosis and treatment.
- Mission 4: By 2030, quantum navigation systems, including clocks, will be deployed on aircraft, providing next-generation accuracy for resilience that is independent of satellite signals.
- Mission 5: By 2030, mobile, networked quantum sensors will have unlocked new situational awareness capabilities, exploited across critical infrastructure in the transport, telecoms, energy, and defence sectors.

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[8] https://link.springer.com/article/10.1557/s43577-023-00659-5#:~:text=Although%20RE%20qubits%20show%20excellent,that%20needs%20to%20be%20addressed

Materials for quantum applications are expected to play a fundamental role in delivering the aforementioned missions and positioning the UK as a key international player in the development of quantum technologies of the future.

In response to the National Quantum Strategy M4QN with the support of the Henry Royce Institute (Royce) commissioned IfM Engage to design and deliver a roadmapping workshop with the following aims:

- Agree the **future directions** that address challenges in the context of three technology areas: Computing and Communication; Sensing and Imaging; Positioning, Navigation and Timing (PNT). The roadmap would help to inform case studies for future investment by the government. The case studies should address the '**what next**' question that is needed for defining funding programmes and materials investment. Specifically:
    - The roadmap should identify relevant materials challenges impeding the development of quantum technologies and establish links between materials and the Quantum Strategy goals/missions.
    - The roadmap can be used as a vehicle for communicating with policy holders.
    - The roadmap will help to determine where funding is needed to support delivery of the Quantum Strategy.
    - The roadmap should include the developments needed for across the board materials for quantum definition.

The main outputs are summarised in the following sections.

Computing and Communications

KEY OUTPUTS

Background

Quantum computing has the potential to significantly outperform any classical computation, enabling hitherto intractable problems to be solved. In classical computers, the basic computational unit is a bit, which is binary and can only hold positions of 0 or 1. In quantum computing, a basic unit is a quantum bit – qubit, that is governed by principles of quantum mechanics. Qubits generally exist in superposition of two basis states, 0 and 1, and remain in this state until observed and measured.

Two qubits can correlate their measurements with each other, which is the state of entanglement. When qubits are entangled the quantum state of each particle of the group cannot be described independently of the state of the others, including when the particles are separated by a large distance.

Quantum computers have the potential to make a great impact in areas of optimisation, quantum simulation, cryptography, searching and quantum machine learning.

Quantum communication leverages both entanglement and superposition to allow more secure communication using quantum key distribution (QKD). QKD involves sending encrypted data as classical bits over networks, while the keys to decrypt the information are encoded and transmitted in a quantum state using qubits[9].

Although quantum computers do exist today, their full potential is impeded by numerous challenges, including scalability, and the quality of qubits and gates (i.e., associated rates of errors). To realise large-scale fault-tolerant computing systems, significant advancements are required in material science and engineering, fabrication and synthesis techniques and new measurement and characterisation techniques.

Key challenges

Forty-four (44) challenges were collected via desk research and participant input prior to the workshop on the Computing and Communications technology area. During the workshop the participants reviewed, edited, and prioritised the list of challenges. The prioritisation was conducted via voting, with each participant voting on their top eight priority challenges. The priority challenges that emerged were reviewed and, where necessary, clustered by topic as similarities appeared between some of these emerging priorities.

The results led to the identification of the following seven key challenges that were explored in depth during the workshop. These are listed in priority order below.

Table 1: List of challenges in priority order for the Computing and Comms technology area

Challenge	Rank
Low temperature electronics integration[10]	1
Enabling quantum transduction and frequency conversion for interconnecting qubits and QPUs[11,12]	2

[9] https://books.google.com/books?hl=en&lr=&id=KF5iEAAAQBAJ&oi=fnd&pg=PA61&dq=quantum+computer+working+principle&ots=R2TNAAVQJP&sig=_q6NTf8VIxehP-8UZkGqF-PStBI
[10] https://iopscience.iop.org/article/10.1088/2633-4356/ac55fb/meta
[11] Materials challenges and opportunities for quantum computing hardware (science.org)
[12] https://iopscience.iop.org/article/10.1088/2633-4356/aca3f2/pdf

Characterisation of performance and routes to noise resilience including against correlated error[11,12,13,14]	3
Developing and maintaining characterisation tools for quantum platforms and metrology[15]	4
Micro and Nanofabrication challenges of control and positioning for technologies on solid state[16]	5
Efficient photonic integration of solid state quantum emitters[11,17]	6
Investigation and discovery of new qubit systems including 2D, topological and spintronics systems[10,11,18]	7

Scalability (1M+ qubits) for fault-tolerant computing was recognised as the final **vision** for the Computing and Communications technology area. The full list of challenges reviewed by the participants and the votes they received is available in Appendix 3.

Each priority challenge was explored and the key material developments required were identified. Delegates developed a roadmap for each challenge (these are presented in the following section).

Material developments required to address key challenges

In the workshop, participants' votes were collated to identify seven key challenges; the specific material developments required to address each challenge were then explored further in small groups. Each group discussed and developed a roadmap to address a particular challenge. The roadmaps included the following fields:

- Scope and boundaries of the application, indicating aspects that are included and excluded from further development;
- Figures of Merit that need to be achieved;
- Required materials and other enabling technologies;
- Any key enablers such as skills and training, policies, infrastructure, and funding.

The current and future Figures of Merit (FoM) addressing performance requirements for each challenge were also summarised. These were assessed using a linear Likert scale from (1) to (5), where (1) indicates poor performance and (5) indicates excellent performance. The FoMs were derived separately for each material development explored. Some FoMs outlined in this report were presented to all participants for consideration and inclusion in the wider discussions if it was deemed appropriate. One topic, 'Develop and maintain characterisation tools for quantum platforms and metrology' did not have any FoMs as it related to equipment development and methods for supporting the advacement of quantum technologies.

Some FoMs were common across different challenges and material developments. These were number of qubits per chip (multiplexing), fidelity of transformed qubit, qubit coherence time, temperature stability, crosstalk, isotopic purity; tunability/Inhomogeneity and operating temperature. The first three listed (**number of qubits per chip (multiplexing), fidelity of transformed qubit, qubit coherence time**) are important across multiple developments and should be addressed as a priority by putting in place specific research and technology development activities.

[13] https://www.mdpi.com/1996-1944/16/7/2561
[14] https://onlinelibrary.wiley.com/doi/10.1002/adma.202109671
[15] https://onlinelibrary.wiley.com/doi/10.1002/adma.202107534
[16] https://link.springer.com/article/10.1557/s43577-021-00137-w#Sec2
[17] https://pubs.aip.org/aip/apl/article/118/24/240502/238995
[18] https://onlinelibrary.wiley.com/doi/10.1002/adma.201904593

Table 2 (below) shows the seven common performance requirements, their applicability for each of the material developments, as well as the current performance gap (i.e., 0 = no performance gap, 4 = maximum performance gap).

Table 2: The seven common Figures of Merit (FoM) across six material developments needed. The numbers indicate the current performance gap (i.e., 0 = no performance gap, 4 = maximum performance gap)

FoM \ Material development	Low temperature electronics integration	Enabling quantum transduction and frequency conversion for interconnecting qubits and QPUs	Characterisation of performance and routes to noise resilience including against correlated errors	Defect engineering	Efficient photonic integration of solid state quantum emitters	Investigation and discovery of new qubit systems including 2D, topological and spintronics systems
Multiplexing (on chip qubits) at 4K of 1M qubits with 1000 wires; number of qubits per chip; inter-qubit coupling	4			3	3	4
Fidelity of transformed qubit; gate fidelity		1	2			1
Transfer time; qubit coherence time/number of gates; latency/delay		2	3	1	3	
Cryo-compatibility i.e. how many transducers before qubits get too hot. Temperature stability; Q = T1/τ		2	2			3
Crosstalk minimisation; inverse error rate in the number of transfers including added thermal noise		2	1			
Isotopic purity; tunability/inhomogeneity			3	3		
Operating temperature				2		0

Topic 1: Low-temperature electronics integration

Definition and scope

This topic is split into three subsets - HEMT amplifiers, CMOS multiplexing and thermometry. The ten-year vision is to have a million qubits multiplexed.

Current challenges

The first subset examines HEMT amplifiers for single photon detection. Specifically, increasing from 10% photon detection in these two to ten gigahertz regions; needing to achieve low temperatures in single photon detection in that same frequency band; and expanding that frequency band by up to approximately forty gigahertz. Alternatives might need to be considered to HEMT to mitigate heat dissipation. And an exploration of other materials that could be used in the longer term may also be required.

The second topic looks at multiplexing and CMOS for multiplexing. The long-term aim is to multiplex a million qubits, however, in order to reach this goal one thousand wires each would require one thousand signals being multiplexed. There are obvious limitations of CMOS in achieving this at low temperatures and alternative approaches should be investigated with potentially new materials, such as Rapidly Single Flux Quantum (RSFQ). Additional consideration is required on how to transition from lacking that level of multiplexing to attaining large grid multiplexing capability.

The third track is thermometry. Obtaining and developing primary standards based on Coulomb blockade, etc., is urgently required. It may be more of a calibration consideration, which NPL could address further.

Key figures of Merit

The key Figures of Merit for this topic are Microwave single photon detection, Multiplexing at 4K of 1M qubits with 1000 wires, Primary thermometry at <1K and Multiplexing with optical/NIR.

Key enablers

The quantum community would potentially benefit from increased communication and collaboration with astrophysics or similar communities about the instrumentation they use.

In terms of skills and training, links should be forged with planetary science, space science, and electronics communities that may be developing similar solutions, but not for quantum-based applications.

Figures 4 and 5 (below) show the roadmap and the current and future performance requirements to address the challenge of low-temperature electronics integration.

Low temperature electronics integration (4K & lower)		**What's IN Scope:** Electronic aspects of integration with qubits **What's OUT of Scope:** • Waveguide/fibre integration • Heat dissipation & performance of optical single photon detectors	**Desired future (key figures of merit):** • Single photon detection 2-10GHz, and → > 40GHz at <4K • Multiplexing at 4K of 1M Qubits hg 1000 wires • Establishment of primary thermometry <1K • Integration of multiplexing with optical single-photon detectors
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
2D materials			
Molecular material			
Semiconductor and photon			
Solid state defects			
Spin and topology			
Superconductors			
Other	Alternate materials to reduce dissipation		
Enabling Technologies	HEMT Amplifiers - 10 photons, 2-10GHz (heating restrictions) → 1 photon 2-10GHz CMOS Multiplexing (Temporal, Spectral): 60K (commercial), 4K (research - heat dissipation issue) → Solutions: superconducting integration, RSFQ - rapidly-switched flux quantum (all platforms), transduction to optical Thermometry - Develop CB thermometer, measure Planck spectrum	Multi-photon >10GHz → Single photon >10GHz → >40GHz 2D/…/Alternatives to CMOS for multiplexing	
Skills and Training	• Connection with other communities: Atmospheric/Planetary Science (similar solutions needed) & Electronic Devices (development of alternative solutions) • Training in cryogenic/electronic skills	• Large scale filtering of electrical signals (fewer wires from RT, more control at low temperatures) • On-chip filtering	
Policies	Skills pipeline		
Infrastructure		Cooling power of cryogenics	
Funding	• Purchase of CMOS multiplexing (work with manufacturers) • Alternative materials to HEMTs (Hub, EPSRC) • New materials to CMOS - RSFQ, Research Programmes (Hub, EPSRC) • NPL/UKRJ - standards	• Alternative materials to HEMTs (Hub, EPSRC) • New materials to CMOS - RSFQ, Research Programmes (Hub, EPSRC) • NPL/UKRJ - standards	
Other			

Figure 4: Roadmap for Low-temperature electronics integration (4K and lower)

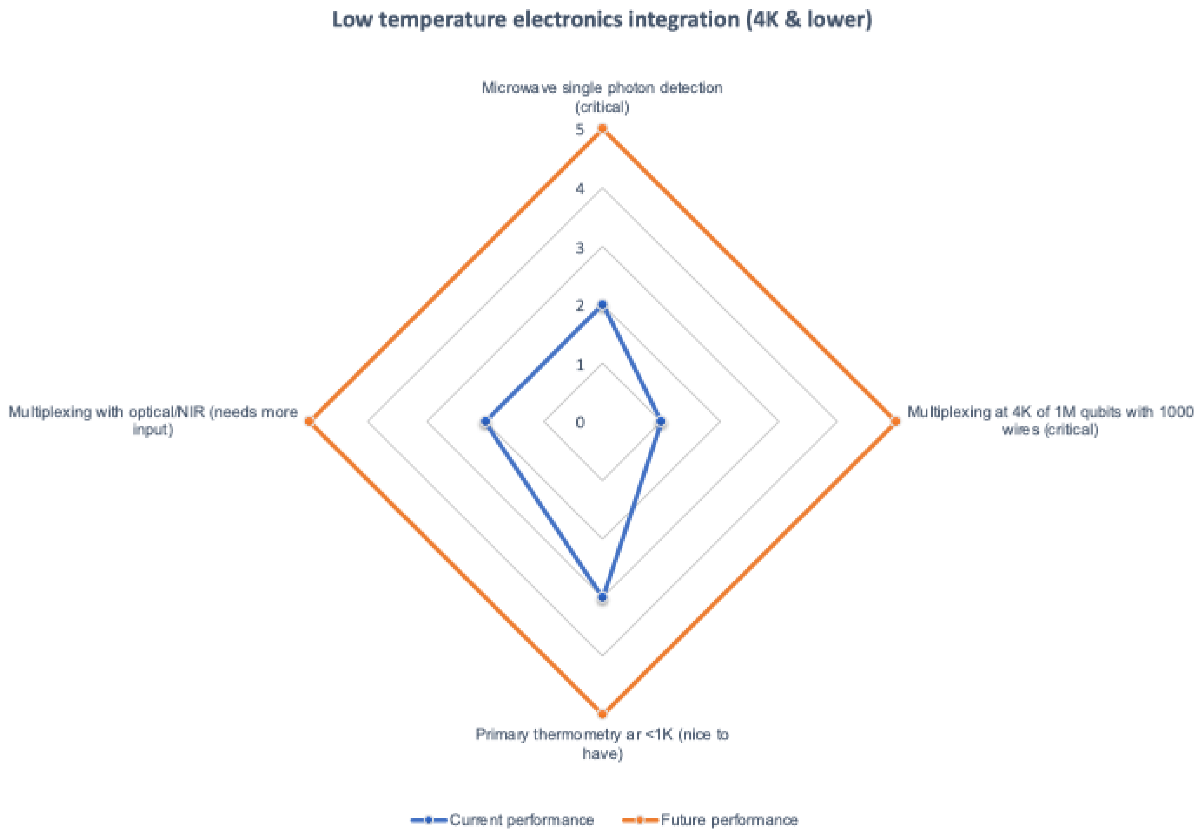

Figure 5: Current and future performance requirements for Low-temperature electronics integration (4K and lower) (5 = excellent performance, 1 = poor performance)

The intermediate targets for achieving the desired final performance are shown in the table below.

Table 3: Intermediate targets for achieving the desired final performance for Low-temperature electronics integration (4K and lower)

	Current	3 years	5 years	10 years
Microwave single photon detection	10 photons 2-10GHz		1 photon 2-10GHz	1 photon 2-40GHz
Multiplexing at 4K of IM qubits with 1000 wires	Not available	Multiplexing at ≤ 4K	Multiplexing of 10 signals	IM with 1000 wires
Primary thermometry at <1K	Noise thermometry nyquist in metals			Primary thermometry with Coulomb blockage & Plank Spectrum
Multiplexing with optical/NIR	5-pixel array with one control			1000 x 1000 array

Topic 2: Enabling quantum transduction and frequency conversion for interconnecting qubits and QPUs

Definition and scope

Quantum transduction, the process of converting quantum signals from one form of energy to another across disparate physical systems.[19,20] This is a fundamental technology for quantum computing and information science

Current challenges

Quantum transduction will be very significant, especially quantum transduction or frequency conversion for interconnecting qubits in different cryostats or different quantum processing units. There are already a range of different qubit platforms available, for example single spin systems, superconducting qubits, atoms, ions. Each of them is often capable of microwave transition or microwave splitting between some of their states, which can then be transferred to an optical state, allowing for easy transfer without added thermal noise between two separated cryostat systems.

Key figures of Merit

The main Figure of Merit in this area is the transduction efficiency i.e. the efficiency of taking a qubit state from the qubit to the optical photon. For such a conversion fidelity is important i.e. the fidelity of that transferred qubit compared to the initial qubit. The transfer time is another critical aspect. As latency can pose challenges, the transfer time from the qubit state onto the photon, needs to be faster than the qubit decoherence time.

The compactness and the topology of the conversion system matching with the qubit system is also very important and everything must be cryo-compatible. Currently all materials that are under development are relevant, although there are not all at the same maturity level. Some materials may be implemented at

[19] https://iopscience.iop.org/article/10.1088/2058-9565/ab788a
[20] https://doi.org/10.1007/s12045-022-1465-4

later times depending on which qubit technology has been chosen at that point, and which is the best one with which to operate.

In the short term, current efficiencies are extremely low at the 10^{-6} level, and these must increase, reaching to as close to one as possible. There is a range of enabling and supporting technologies needed such as optomechanical interactions, piezoelectric and nonlinear materials and a moving away from bright optical and microwave sources. The aim would be to be working towards the single photon level in five years with the transduction efficiency moving from 10^{-6} up to 1 efficiency.

Cryo-compatibility may pose a challenge. Numerous tests so far have been held at room temperature with bright light rather than at a low temperature, which is required where one does not add any thermal noise into the system.

Key enablers

The main enablers are skill shortages especially multidisciplinary training across different areas e.g. quantum, microwave and optical. Specific training in metrology and testing is also required. Standardisation of the different underlying qubit technologies would also be useful. Specific infrastructure on nano/micro fabrication facilities for integration and demonstration purposes and scaling-up fabrication to commercial volumes is also essential as well as access to a dark fibre network.

Figures 6 and 7 (below) show the roadmap and the current and future performance requirements to address this challenge.

Enabling quantum transduction and frequency conversion for interconnecting qubits and QPUs		**What's IN Scope:** Qubit <-> Microwave <-> optical Spin, superconducting atom, ion Coax, stripline free space Fibre waveguide free space	**Desired future**
		What's OUT of Scope: Moving physical qubits is not in scope	**Figures of Merit**
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
2D materials			
Molecular material			
Semiconductor and photon			
Solid state defects			
Spin and topology			
Superconductors			
Other			
Enabling Technologies	Semiconductor and photon Superconductors Microwave and optical cavities + metamaterials -> tempered & spatial confinement -> Strong coupling Current efficiencies are 10 to the -6 -> we need 1 Optomechanical interactions -> piezoelectric, nonlinear materials Currently uses bright optical + microwave sources	Integration of solid state spin defects with microwave and optical resonators ODMR development + characterisation of qubits Determine which defects have correct energy level structure (unequal) Move to single (microwave and optical) photon level	Majorana <-> microwave transitions?? Chirality + polarisation useful/required?? System level interconnection of >2 QPUs in separated cryo-systems (same lab? different buildings?)
Skills and Training	Hybrid training qubit + microwave + optical Classical control technology meets quantum (comms, RF, cryo. etc)	Trained in metrology + testing of devices	
Policies	Enabling international researchers to enter the UK (visa help)	Standardisation of underlying qubit technology Qubit frequency/choice	
Infrastructure	Control/ fast RF electronics Cryostats in required I/Os Mechanical stability DP closed-cycle dilution refrigerators	Nano/micro fabrication facilities for integration Scaling to commercial fabrication	Dark fibre network access
Funding	Investment in new materials + systems early! (Feeds into missions) Large infrastructure (fridge + RF equipment) for demos	Government procurement of prototype	
Other			

Figure 6: Roadmap for Enabling quantum transduction and frequency conversion for interconnecting qubits and QPUs

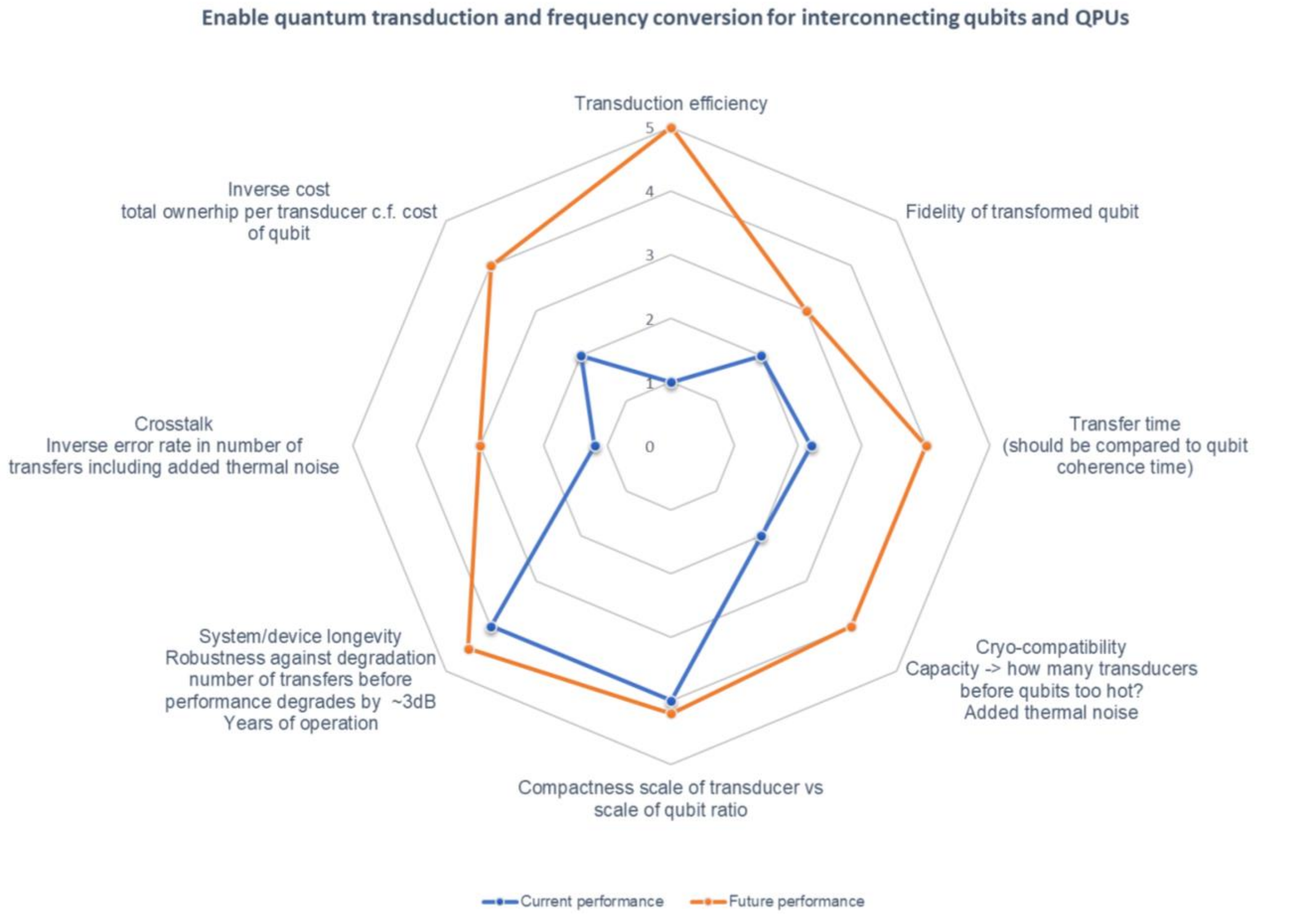

Figure 7: Current and future performance requirements for Enabling quantum transduction and frequency conversion for interconnecting qubits and QPUs (5 = excellent performance, 1 = poor performance)

Topic 3: Characterisation of performance and routes to noise reduction. Resilience

Definition and scope

Noise and the factors that contribute to it, is a very important topic in quantum computing and communications. The critical factors when considering noise across different computing platforms are coherence time and the number of gates. An initial agreed target is that 10^{-6} gates per coherence time are needed. The current state-of-art is halfway to that level, depending on the platform. Gate fidelity is also a key factor. Some good progress has been achieved in this area although it is very much dependent on the platform used.

Current challenges

There are several factors that contribute to coherence. Some of those are for example, crosstalk, which depends on temperature stability, electromagnetic interference, electric noise and contaminants and defects within the material itself. Interface quality is also a factor and to some extent isotopic purity depending on the material. Many of these are considered cross-platform issues and are therefore somewhat lower priority. For example, electromagnetic problems will not be known until larger systems are constructed. However, crosstalk has known solutions and progress has been made in that area, so there are different aspects on which research effort can focus.

In the short-term research activities should involve co-operation and co-ordination with other research communities, for example the atomic coherence control community and the NMR control community. These groups are developing and using different techniques from the quantum research community and cross-fertilisation of ideas and methods could help achieve a much tighter and faster turnaround between characterisation and fabrication. Co-operation will also help the use of automated systems to take measurements and receive feedback.

Key figures of Merit

The key figures of merit are coherence time/number of gates, gate fidelity, crosstalk minimisation, and temperature stability.

Key enablers

Specific infrastructure needs in this area include a laboratory to manufacture and scale-up systems. There is also a requirement to build up specific partnerships to compensate for critical capabilities that are lacking in the UK presently. Enabling technologies include automation of advanced characterisation techniques.

Figures 8 and 9 (below) show the roadmap and the current and future performance requirements to address this challenge.

Characterisation of performance and routes to noise reduction. Resilience		What's IN Scope: What's OUT of Scope:	Desired future Figures of Merit
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
2D materials		• TMD	
Semiconductor and photon		• High quality III-V semiconductor growth • Strain engineered III-V semiconductor structures	
Solid state defects			
Spin and topology		• Topological insulators • Topological crystalline insulators • Topological semimetals	
Superconductors			Topological superconductors (Majorana fermions)
Other	Link atomic covalent control and NMR covalent control communities	• Tight and fast turnaround between fabrication and characterisation, including more advanced characterisation techniques • Produce characterisation data at scale (automation of measurements, use ML to characterise large data sets)	Rigorous studies of parasitic entanglement between qubits and long-lived noise states
Enabling Technologies	Scanning thermal microscopy that can image local temperatures	• Development of error correction algorithms (dynamically decoupling) using machine learning • Automation of advanced characterisation techniques • Study of electronic noise from surface states • Scanning nano SQUID	
Skills and Training	• Closer cooperation between communities working on error correction algorithms (theory) and implementation (experiment) • Improved conditions for early career researchers (better PhD stipends, post doc salaries)		
Policies	• Isotopically pure material held by other countries - build up national reserves • Identify critical capabilities not available in the UK and map supply chain		
Infrastructure		• Modelling and high performance computing • Versatile multinational fab for prototyping hybrid devices	
Funding	• More flexible funding schemes for capital equipment (up to £400k) • Prosperity partnerships with start-ups • Target discipline hopping for electrical engineers to work in quantum	• Closer cooperation between communities working on error correction algorithms (theory) and implementation (experiment) • Improved conditions for early career researchers (better PhD stipends, post doc salaries)	

Figure 8: Roadmap for Characterisation of performance and routes to noise reduction. Resilience

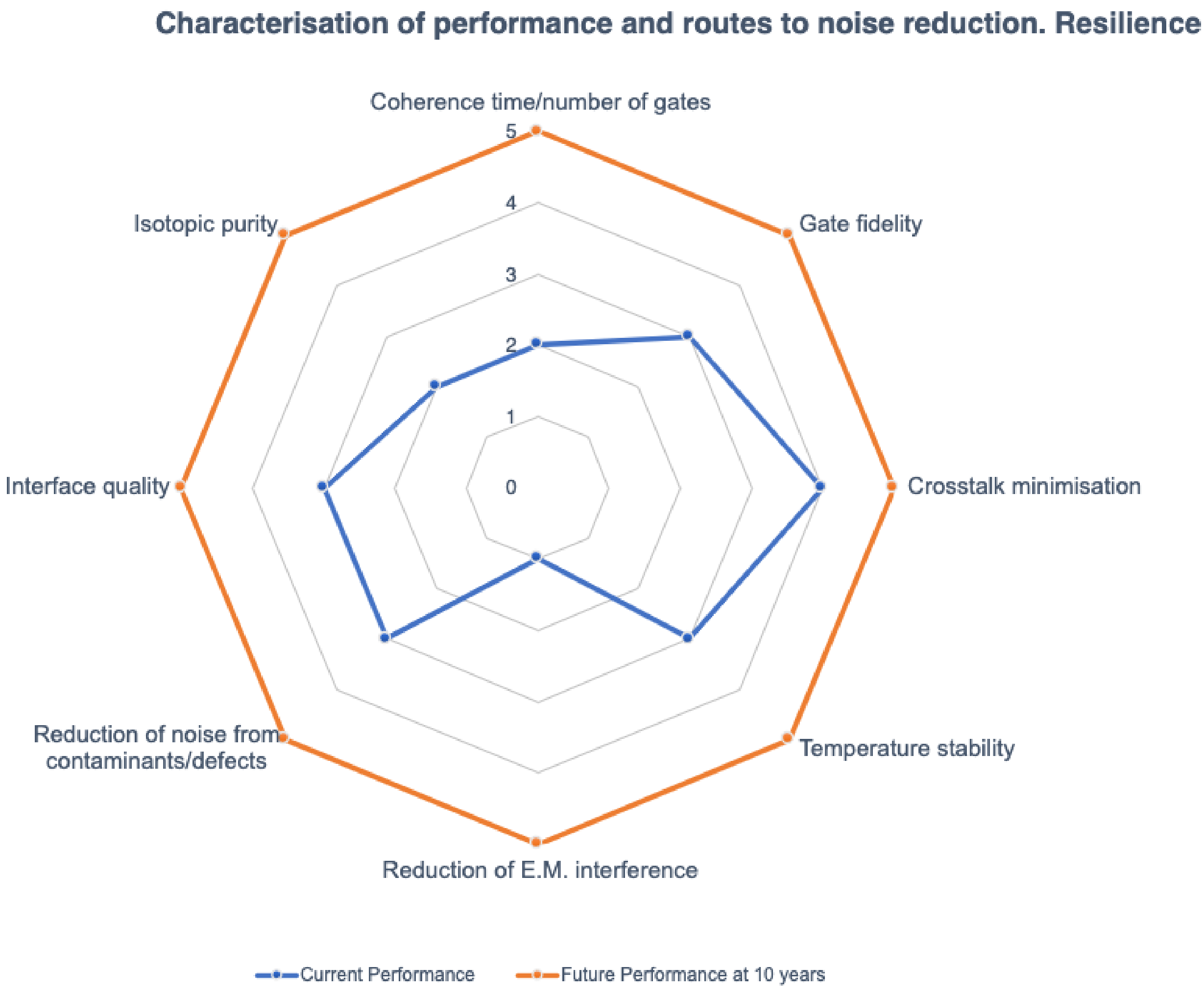

Figure 9: Current and future performance requirements for Characterisation of performance and routes to noise reduction. Resilience (5 = excellent performance, 1 = poor performance) Ref: Figures of merit derived from ref: https://www.science.org/doi/10.1126/science.abb2823

Topic 4: Develop and Maintain characterisation tools for quantum platforms and metrology

Definition and scope

Characterization tools and platforms are a necessity to assess the properties of all materials developed for quantum technology applications. It is therefore vital to develop and maintain existing facilities for spectroscopic and characterization methods and to promote the formation of new facilities where such facilities do not currently exist in techniques that may be used to assess quantum materials. The wide range of potential materials for quantum applications, both sensors and sources, necessitates access to an equally large number of tools for characterization.

Current challenges

An initial action must be to identify as a community where current facilities are already present, if these facilities are suitable for the study of quantum materials, what support is needed for these facilities and what improvements could be made to make them more suitable. Where suitable facilities do not currently exist these gaps must be identified. Plans to work towards maintaining and upgrading existing facilities and establishing new required facilities in methods and techniques that are important for characterizing materials for quantum technologies need to be developed. Identified technologies can be broken down into three categories: Magnetic Resonance including: Electron Paramagnetic Resonance (EPR), also known as Electron Spin Resonance (ESR), Nuclear Magnetic Resonance (NMR) and Optical Magnetic Resonance (OMR). Diffraction and scattering methods including: Xray Diffraction (XRD), Xray Photoelectron Spectroscopy (XPS), and microscopy including: Scanning Tunnelling Microscopy (STM), Scanning Transmission Electron Microscopy (STEM) and Tunnelling Electron Microscopy (TEM).

National facilities already exist for EPR (Manchester), NMR (Warwick), XRD (Diamond/Southampton), XPS (Harwell), STEM (Daresbury). A list of EPSRC funded national facilities is availed: https://www.ukri.org/councils/epsrc/facilities-and-resources/find-an-epsrc-facility-or-resource/. In addition, scientists in the field also make use of XFEL sites, ARPES, DIAMOND, ISIS and REUDI facilities. The ability of the current facilities to be able to measure quantum materials samples must be confirmed and any critical gaps identified. Where current facilities are sufficient these should be maintained, so access can continue, and where gaps exist options to fill these should be explored.

Within each characterization technique there will be enabling technologies and challenges that will need to be considered to make the technique more useful for the characterization of quantum materials. For example, within EPR one challenge is the development of higher Q-factor resonators to allow measurements of lower numbers of spins, at the same time spectrometers that con operate at wide frequency bandwidths are needed to allow systems with different g-values to be addressed at the same field and high-field systems may be necessary for higher fidelity measurements and better separation of signals. In microscopy there are challenges related to measurements at lower temperatures with better resolution.

Another current challenge is retaining skilled personnel, the current UK research funding landscape encourages frequent movement of early career researchers, particularly post-doctoral research associates who are often employed on fixed term contracts linked to specific grants. These people are frequently the most skilled personnel in a laboratory setting and thus skills can be lost when personnel move to different positions or are not retained within the sector. A key challenge is how to prevent this loss of skills and retain key technical personnel.

Key enablers

Central resources are required for quantum technologies. Therefore, it will be beneficial to maintain or establish national facilities or virtual national facilities connecting together various different existing infrastructures aimed specifically at quantum and quantum technologies and offering space to explore. Where existing facilities exist, these may not currently be focused towards quantum technologies and therefore additional resources may be required to enable specific measurements for quantum technology materials.

Skills and training is another crucial aspect. There is a need to not only upskill PhD students and early career researchers, but also to maintain skills within this existing community through the establishment of more permanent roles and experimental officers. For example, lab specialists, or maintenance technicians for high-value pieces of equipment need to be financed in permanent roles so these capabilities do not suddenly become defunct. If the long-term goal is to establish wider-ranging communities or virtual national facilities, skill sharing must be embedded within those national facilities. Upskill personnel should not just be in one specific area, but across different research and application areas. Sharing of skills is one way to prevent skill loss in the sector, another would be to look to maintain and establish permanent technical posts in key areas, linked to national or virtual national facilities.

The infrastructure should extend into materials imaging, spectroscopy and analysis. There are also requirements for high throughput photon/spin material assessment capabilities, for example in spin-resonance techniques such as EPR, NMR and OMR, and optical metrology. Access to advanced analysis techniques such as in situ XRD, XPS, STEM, TEM is also important. It is vital to build on and improve the current foundation of existing facilities by ensuring adequate funding to maintain and improve these and where necessary provide specific funding to allow focused efforts for quantum technologies and measurement. This is in addition to seeking funding for the establishment of new facilities or virtual facilities in techniques where is currently no provision.

Figure 10 (below) shows the roadmap and the current and future performance requirements to address this challenge.

Develop and Maintain characterisation tools for quantum platforms and metrology		**What's IN Scope:** • Spin characterisation • Material characterisation → Identify best platforms **What's OUT of Scope:**	**Desired future** **Figures of Merit:** • feedback loop → FoM from other priorities: Can characterisation meet these FoM? • Scalability, Noise
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
Other	• Sensor materials • Source materials (e.g. superconducting sensors, 2D materials)	Input from other priorities to define the required characterisation methods in medium to long term ↓	
Enabling Technologies	• ESR, STM, NMR, OMR • Low noise electronic components (e.g. cryogenic amplifiers etc.) • Higher Q resonator system for measurement of low number of spins • Noise … measurement technique • Incorporation of quantum technologies in existing technology/techniques • Low temperature and higher spatial resolution microscopy and imaging	• Higher fidelity/frequency • Higher power • Shorter pulses • Higher resolution • Extension of techniques to new … (e.g. higher frequencies/fields)	Being able to measure required quantum figures of merit
Skills and Training	• Student/PDRA training on different disciplines through centres/virtual quantum facilities, retaining PhD students • Supporting early career researchers. Early career researcher training/workshops in quantum sensing • Better integration with sensing communities to improve characterisation methods in long term • Low temperature and higher spatial resolution microscopy and imaging	• Increased … /PDRA/Education level to maintain capabilities • Skills swaps between facilities- upkeep over time (e.g. within virtual national facilities) • Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements	
Policies	• Make the most of current opportunities • Quantum government policy (S+T framework) • Framing/pitching … so … … brand as "UK based" • Low temperature and higher spatial resolution microscopy and imaging	• International collaboration to … down time of national facilities - e.g. diamond • Policy for international partnerships to draw in critical capabilities and build supply chain opportunities • International Partnerships and Collaboration especially for fabrication facilities for all of the potential hardware platforms	
Infrastructure	• Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities • Establishing collaborative networks in academia with input from industry and research institutions to foster knowledge exchange and interdisciplinary research. • Establish interdisciplinary research teams with chemists, materials scientists quantum physicists and engineers • National Quantum Computing Centre • Access: XFEL, ARPES, DIAMOND, ISIS, REUDI • Low temperature and higher spatial resolution microscopy and imaging	• Dedicated facilities for quantum • Improved/new access routes for virtual national quantum facilities • Translation to low noise environment	
Funding	• EPSRC/UKRI strategic equipment for single lab systems • Funding to employ senior research associates in national facilities able to produce service work and ensure continuity of equipment. A higher level of senior researcher involvement is needed in the growth and processing of materials	• Funding for national/virtual national facilities building on existing capabilities + senior research associates • Adequate funding from various bodies in research grants to support long-term research projects	

Figure 10: Roadmap for Develop and Maintain characterisation tools for quantum platforms and metrology

Topic 5: Defect Engineering

Definition and scope

The aim for this topic is to move towards production of wafer-scale crystalline dielectric materials with engineered crystal defects for use as physical qubits in quantum sensing, communications and computing. Defects provide localised atom-like systems with coherent electron spins which couple to nuclear spins both within the defect itself and in the surrounding material. The aim is to produce patterns of defects which are accurately (10-100 nm) positioned so that they can be integrated with electronics and photonics for initialisation, control and readout, and their coherence properties optimised by minimising perturbations from the surrounding crystal environment. Such defect-based systems are amongst the most promising for achieving scalable quantum computing, their small physical size enabling a million or more qubits to be situated on a single chip. The engineering of passive defects in these materials and devices to control other aspects of the crystal environment that impact qubit or system-level performance is also in scope.

Two broad classes of point defects are highlighted as promising qubit systems – simple paramagnetic impurities, such as phosphorus in silicon, which act as shallow donors or acceptors; and colour centre defects, such as the nitrogen-vacancy defect in diamond, which offer deep gap electronic states with optical transitions that facilitate coupling to an optical network. The challenges presented by these two classes of defect-engineered materials are different and will be discussed separately within this topic.

Common factors that impact the development of technologies utilising these two classes of defect qubit systems are the growth of large, high quality host crystals, impurity implantation and annealing, surface passivation, strain control, and charge state control. Characterisation and modelling on multiple length scales from atomic to mesoscopic are also important.

Current challenges

For both systems, two main areas are identified where further research is required. One is the coupling between electron spin qubits. In donor-based systems, this requires the positioning of impurities with sub-100 nm accuracy[21], while in colour centre-based systems the challenge is the realisation of efficient spin-photon entanglement. Considerable research effort is currently dedicated to these topics, which comprises advancement of the implantation, annealing, and surface conditions for different types of defects, as well as the fabrication of photonic devices for efficient coupling of photons.

Another area where there is a significant separation between what is currently achievable and what is required for useful applications is the number of qubits per chip. All current research is focusing in making well-controlled systems and producing one or two of those systems on a chip. The goal to reach production of at least 10^6 working qubits on a chip is likely to require sustained effort beyond the realisation of smaller working systems due to the extreme precision required. Issues of cross-talk between qubits, connectivity of control systems and power dissipation will need to be considered carefully.

With colour centre-based systems, some of these challenges could be lessened by the identification of new defects with superior properties, combining efficient and stable optical transitions with long-lived electron spin coherence and convenient methods for qubit control. Some initial efforts have been made to establish the design rules for such defects and to identify promising host materials, but the theoretical understanding of how defect structure translates to properties is far from complete and the parameter space is large. This is fertile territory for fundamental research both in experimental studies and in ab initio modelling. Where promising properties are observed experimentally, new characterisation techniques to identify the physical structure of individual defects are also required.

For known defects which display sufficient physical attributes, methods for controlled defect generation and for integration into devices are a key focus. Much of the functionality demonstrated to date has been proof of concept, requiring careful selection of individual defects with little consideration of fabrication yield which will be important for scalable technology. This presents challenges with regards the infrastructure and personnel resources needed to develop high levels of process control, particularly in the context of university-based research. Sustained effort and investment in defect engineering and dedicated device fabrication for host materials such as diamond will be essential.

Key figures of Merit

Some key figures of merit for defect-based quantum technologies are identified below. Note that there are many interdependencies and important nuances not described here which require consideration in any detailed analysis.

Coherence time – the time scale over which coherence has been demonstrated, including the use of dynamic decoupling techniques. Currently ~1 s for electron spins and ~1 minute for nuclear spins.

Single qubit gate time – typically ~10 ns for electron spins and ~10 μs for nuclear spins, useful for comparison with other physical platforms.

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[21] Current flip-flop architecture relaxes previous requirements of sub-10nm accuracy

Debye-Waller factor/coupling efficiency – this FoM pertains to colour centres and indicates the relative level of challenge in realising efficient spin/photon entanglement.

Operating temperature – the temperature above which thermally induced decoherence limits performance.

Tunability/inhomogeneity – indicates the relative degree of challenge in scaling up to large systems. Sufficient tunability to compensate for inhomogeneity is desirable. Relates both to the defects and to the quality of the host material.

Positioning accuracy of defects – indicates the level of challenge in scaling up to large systems. Different requirements for different device architectures.

Number of qubits per chip – a key engineering FOM indicating current status and future potential for scalable technology. Relates to size of physical qubits and control system architecture, as well as advancement of chip fab processes.

Single qubit gate error – indicates readiness/potential for performing quantum logical operations. Error rates <10^{-3} are generally considered necessary: important to understand origins of errors in cases where this condition is not yet met.

Key enablers

The range of expertise and infrastructure needed to enable this development are listed below. The principal unmet need is for an advanced device engineering facility which brings together the various processing steps in a foundry format. Such an entity would support both university research and commercialisation activity and would serve to cement the UK's position of leadership in this field. A growth in supporting research in defect engineering, materials characterisation at the single defect level, and ab initio modelling of crystal defects (especially of electronic excited states and decoherence mechanisms) will also be important to provide a feedstock of new science in the longer term.

Figures 11 and 12 (below) show the roadmap and the current and future performance requirements to address this challenge.

Defect engineering. It addresses the Micro and Nanofabrication challenges of control and positioning for technologies on solid state (scalability: materials fabrication, defect positioning, materials quantity)		**What's IN Scope:** Surface passivation, overgrowth. Defect design. Growth, implantation & annealing. Characterisation of qubit defects. Colour centres, single donor/acceptor systems, rare earths. Couples defects. **What's OUT of Scope:** • Device integration • Active noise suppressing techniques • Transduction	**Desired future (key figures of merit):** • Coherence times • Debye-Waller factors • Operating T • Tunability • Spatial positioning accuracy • Single qubit gate times • Wafer scale fab • Gate fidelity
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
Solid state defects	• Diamond, SiC, Si • Charge state control • Isotope selection in host material • Restoration of quantum quality material post-defect fabrication	• Strain engineering • Coupled defects • Defect orientation • Isotope engineering • Restoration of quantum quality material post-defect fabrication	• 2D materials? • ZnO • 12" Wafer scale homogeneous defect-based chips
Enabling Technologies	• Ion implantation • CVD wafer growth • Laser processing • Rapid throughput fluorescence charm • Hydrogen lithography for atomic precision implantation • Tight binding • Atomistic modelling: DFT, MD • Doctoral training at interface of materials & quantum tech - defects science and engineering • Industry engagement & sponsorship of training programmes • Enable partnerships for supply chain & critical infrastructure/fab facilities • International/Visa changes • Modelling of new materials & devices/ HPC • Nano fab. Foundry • Pilot production facility • Diamond fab • Funding of senior Ras/technicians for long term continuity & consistency in materials growth & processing • International funding • Sustained long term effort, renewable grants	• Quantum sensors for defect analysis • Synchrotron for Xray spectroscopy • Defects by design Sustained long term effort	• ESR of single spins? • ESR/STM
Skills and Training			
Policies		Skills pipeline (from Year 7)	
Infrastructure		Cooling power of cryogenics	
Funding	• Purchase of CMOS multiplexing (work with manufacturers) • Alternative materials to HEMTs (Hub, EPSRC) • New materials to CMOS - RSFQ, Research Programmes (Hub, EPSRC) • NPL/UKRI - standards	• Alternative materials to HEMTs (Hub, EPSRC) • New materials to CMOS - RSFQ, Research Programmes (Hub, EPSRC) • NPL/UKRI - standards	
Other			

Figure 11: Roadmap for Defect Engineering

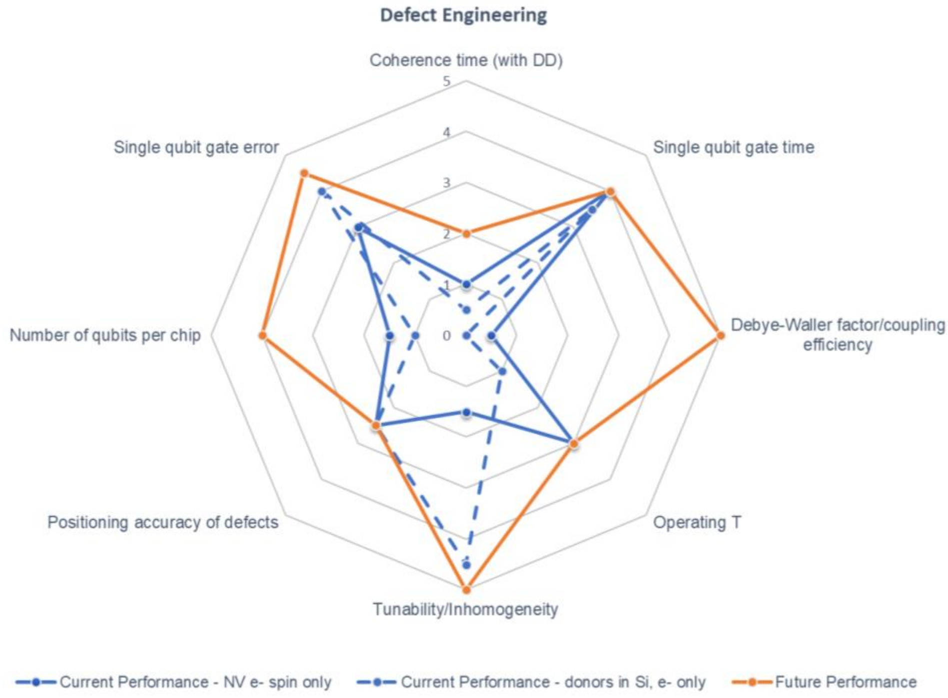

Figure 12: Current and future performance requirements for Defect Engineering (5 = excellent performance, 1 = poor performance)

The intermediate targets for achieving the desired final performance are shown in the table below.

Table 4: Intermediate targets for achieving the final performance for Defect Engineering

	Level 1 (Now)	Level 2 (3 years)	Level 3 (5 years)	Level 4 (7 years)	Level 5 (10 years)
Coherence time with DD. e (n)	1 s (1 min)		10 s (10 min)		100 s (>1 h)
Single-qubit gate time	30 ns		10 ns		3 ns
Single-qubit gate error	10^{-3}		10^{-4}		10^{-5}
Two-qubit gate time	10 μs		3 μs		1 μs
Two-qubit gate error	10^{-2}		10^{-3}		10^{-4}
Spin/photon coupling efficiency	0.3	0.8	0.9	0.95	0.99
Operating T	4 K				77 K
Positioning accuracy of defects	10 nm				
Number of qubits per chip	1	100	10^4	10^6	10^8

Topic 6: Efficient photonic integration of solid state quantum emitters

Definition and scope

This topic predominantly addresses the challenge of achieving efficient, photonic integration of solid-state quantum emitters. It excludes the challenge of transduction or defect engineering, as these are addressed separately.

Current challenges

There are two important challenges in this area. The first is maintaining the coherence properties of the defects/ions after nanostructuring the material. The second is multiplexing; independently manipulating multiple qubits, both photonics and matter qubits (e.g. atoms, spins).

Key figures of Merit

In the Figures of Merit, primary loss is a critical consideration, whilst in classical communications this is less significant because those can simply amplify their signals. However, in quantum communications it is critical that every fibre interconnect, every interface between the photon and wave guide or optical mode is perfect and can be manufactured regularly, and in a repeatable way. The constraints for quantum systems are much higher than those that currently exist in optical networks. There were certain other facets of the network that may also be important such as polarisation maintenance, depending on the entanglement schemes.

Beyond the polarisation extinction ratio, latency is also an important factor. If a considerable time period were to elapse before a detected signal could be fed back into a control system, (in order that photons may be rerouted through an extended optical network), the process would be unviable. This must be done quickly, so there should not be any latency induced by the interface.

Other Figures of Merit would normally be specific to the physical system selected. Nonetheless, latency in terms of the decoherence time of the qubit that one might couple into the network, would be a common Figure of Merit across different physical systems. Ideally, latency should reduce to below a microsecond, but that would require extensive research effort.

Depending on the physical system, latency should be much quicker than the decoherence time. Ideally, the latency of signal through a system is perhaps a thousandth of the decoherence time. Latency has a polarisation extinction ratio, so generally fibres can maintain 26 dB of polarisation extinction ratio, with 30 as a significant success. It is estimated that approximately 10 dB can be achieved in an integrated system includes all of the interfaces.

Loss would also be critical for any physical system used. The main contributor to loss is the interface between the emission itself and coupling into a guided mode, in the context of coupling to micro resonators or wave guides.

Detection efficiency is currently not a major issue. Superconducting nanowire single-photon detectors (SNSPDs) can be designed in a way to be parallel to a wave guide and they can increase their efficiencies with existing technology. Shorter-range networks can be developed and operated at frequencies which are closer to the type of qubit used. PsiQuantum for example are focusing in achieving frequency shifts into the C band in the short term. Insertion losses into these components remain high and could be addressed. Finally, multiplexing would be important, ideally doing many of those in slight frequency-shifted ways to utilise fibres.

Key enablers

The main enablers identified were around skills and training and the need for establishing an integrated national skills program for quantum technology that spans across all educational stages. Policy interventions for supporting international partnerships to draw in critical capabilities and build supply chain opportunities is also important. Furthermore, establishing interdisciplinary research teams with chemists, materials scientists, quantum physicists and engineers is essential in this area.

The infrastructure requirements are also critical for enabling both research and but also scalability and manufacture of successful technologies. These need to be supported by additional characterisation and testing facilities and material and device modelling capabilities.

Figures 13 and 14 (below) show the roadmap and the current and future performance requirements to address this challenge.

Efficient photonic integration of solid state quantum emitters		**What's IN Scope:** Photonic integration/miniaturisation Interconnection/telecom network CC-MD31 heterogenous optical interfaces **What's OUT of Scope:** Transduction Defect engineering	**Desired future** Utilising C-band networks to obtain long distance distributed entanglement **Figures of Merit** Link loss Polarisation maintenance / polarisation extinction ratio Latency
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
2D materials	Materials to be compatible with temperature of qubit operation (temperature stability of component operation) Maintaining coherence properties of the defects/ions after nanostructuring the material	Multiplexing -> Independently manipulating multiple qubits, both photonics and matter qubits (e.g. atoms, spins) Entanglement between proximal chips (short inter-connect) Coupling between qubits on same chip (agnostic)	Efficient coupling of photons into fibre -> coherent C-band photons
Molecular material	Efficient coupling into waveguides or microresonators		
Semiconductor and photon	Efficient capture of generated photons (M / nano structuring host material / waveguide material		
Enabling Technologies	Cryogenics -Cost -Base T -Cooling power -Optical interface -Mechanical stability Thin film growth / nanocrystal techniques Development of photonic (nano/micro) structures and materials to enable -High Q-factor of micro resonator; Good mode matching; Retrieve photons in controlled way; Compatible with material platform Single photon frequency conversion (supporting laser development	Integrated: Modulators / RF electronics / Electrical circuits Heterogenous micro-scale integration. Micro mechanical manipulation Low-loss photonic circuits (e.g. laser-written) for routing M-Machining -Dielectrics -Metals	
Skills and Training	Fabrication photonics Training for effective communication Continuous professional development of existing professionals (PhD, researchers, ECR, technicians, industry)	-Engagement with schools, social sciences and arts to maximise engagement of younger generations -Encouraging cross-disciplinary proposals	
Policies	• Integrated national skills program including quantum technology spanning all educational stages and retraining. To incorporate skills such as physics, chemistry, chemical physics, computational modelling, and engineering. Also training specialised technicians • Government-led development of mission-led roadmaps for quantum impact, spanning fundamental research, development, and innovation • Policy for international partnerships to draw in critical capabilities and build supply chain opportunities • Broad-based and strategic approach to communications with tailored messages to inspire involvement in the quantum sector • International Partnerships and Collaboration especially for fabrication facilities for all of the potential hardware platforms • Visa changes to allow new postdocs to move to the UK • Financial support and incentives for local quantum-related industries (policy, tax, tariffs, etc.)		
Infrastructure	• Foundry cleanrooms • Modelling of new materials and devices • Pilot production facilities to bridge the gap between laboratory-scale research and industrial-scale manufacturing • Infrastructure for large-scale manufacturing of 2D materials and quantum device fabrication (fast waveguide switches, high efficiency single-photon detectors) and wafer scale testing. • Nanofabrication facilities • Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities • Testing equipment and protocols	Micro-optical assembly infrastructure	
Funding	• Adequate funding from various bodies in research grants to support long-term research projects (4-5 year length) • Specific grants and funding programs targeting quantum technology and 2D materials research		
Other	• Establishing collaborative networks in academia with input from industry and research institutions to foster knowledge exchange and interdisciplinary research. (Already present) • Establish interdisciplinary research teams with chemists, materials scientists, quantum physicists and engineers (Needs emphasis)		

Figure 13: Roadmap for Efficient photonic integration of solid state quantum emitters

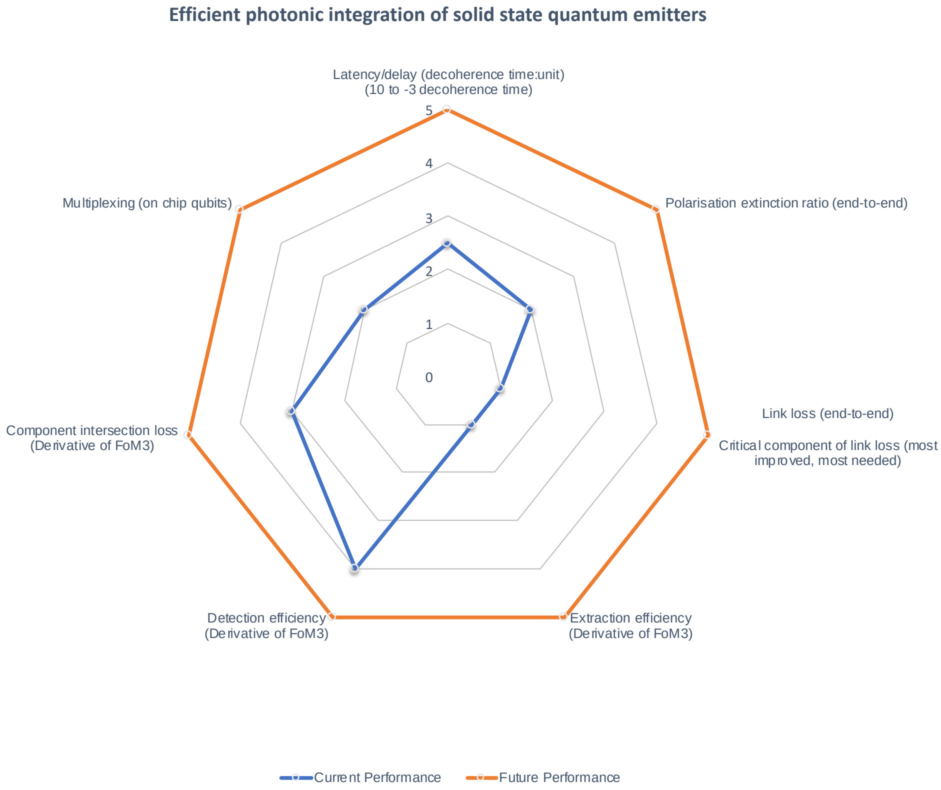

Figure 14: Current and future performance requirements for Efficient photonic integration of solid state quantum emitter (5 = excellent performance, 1 = poor performance).

Topic 7: Investigate and discover new qubit systems including 2D, topological and spintronics systems

Definition and scope

The topic addresses research and investigation into new candidate qubit materials, to address some of the current challenges identified and in particularly the issues with noise and scalability. The main question still remains, if it is better to solve the new challenges that will incur by these new materials or new systems, in order to benefit from the advantages such as longer coherence time, best fidelities and more.

Current challenges

In the short term, the two main challenges are the characterisation of the thermal relaxation time T_1[22] for new candidate materials and the development of new manufacturing tools and protocols. In the medium term, achieving interqubit coupling for certain material systems and control per qubit will be important research developments.

Key figures of Merit

The key Figures of Merit to incorporate would be the quality factors, the number of gates one can do in a T_1 time, which is a coherence-related measure. There exists quite a big deviation from the current state-of-art and the required performance that would enable real-life applications. Another key Figure of Merit is the number of logical qubits one obtains per physical qubit, and the ultimate driver is to achieve a high

[22] T1 is the time needed for a qubit to move from the excited state |1> to the ground state |0>

number of logical qubits. Therefore, one must ensure that new qubit materials have a long Q factor, but also of vital importance is the inter qubit coupling. Some novel materials for example, new 2D material, or an exotic superconductor might be able to achieve a very high-quality factor, but new techniques must develop to couple them together to make two qubit gates, as well as logical qubits.

Transduction is also critical as currently, the frequency range in which qubits formed by these new materials is limited. Therefore, it is important that they can be integrated with other systems. The reproducibility and the manufacturability are also crucial. These act as blockers at the moment with new materials.

It is expected that within the next three years it should be possible to measure the T_1 times of qubits developed by using these new materials. Within the next five years, it is anticipated to be able to implement some of these into qubit coupling using new materials. The materials that would allow this coupling need to be identified and could be conventional superconductors or for instance, or new metal organic frameworks for coupling qubits.

It is important to not incur a cost in complexity in order to scale up. The control lines per qubit should not escalate in order to get them coupling. In ten years on, a factor of ten should be achieved, for example ten physical qubits per one logical qubit. Following on work should then focus on the issues of transduction and integrability. Additional requirements are new synthesis techniques, transfer device assembly, characterisation tools or computational material discovery.

Key enablers

The main enablers needed are new or updated nanofabrication facilities, specific grants leading to flagships, foundries, funding for researching new materials and establishing interdisciplinary research teams and initiatives.

Figures 15 and 16 (below) show the roadmap and the current and future performance requirements to address this challenge.

Investigate and discover new qubit systems including 2D, topological and spintronics systems		**What's IN Scope:** New materials and hybrid systems for: • high coherence and topological protection • complementary functionality combined with high density of qubits • telecom range operation for interconnecting qubits • new ways to control/operate qubits (capability to address qubits individually) **What's OUT of Scope:** Prematurely constraining materials loss (e.g., attacking to Al or GaAs)	**Desired future (key figures of merit):** • T1/gate time = number of operations (better fan out of entanglement) • number of physical qubit to create a logical cubit • energy consumption per logical qubit operation
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
2D materials	Characterising T1/ for prospective materials		
Molecular material			
Solid state defects	Characterising T1/ for prospective materials		
Spin and topology			
Other	Development of new manufacturing tools and protocols	• Interqubit coupling: Metal organic framework - THz (designer transitions), Spin-optical/microwave • Control per qubit • Identify materials in focus (best bets)	• Logical/Physical • Integration/Transduction
Enabling Technologies	• Computational material discovery • Synthesis, Transfer, Device assembly		Synthesis, Transfer, Device assembly
Skills and Training	Modelling of new materials and devices		
Policies	• Government-led development of mission-led roadmaps for quantum impact, spanning fundamental research, development, and innovation • Visa-free M4Q without borders • Collaboration with key partner counties (non EU): Japan, Switzerland, Australia, Canada		Financial support and incentives for local quantum-related industries (policy, tax, tariffs, etc.)
Infrastructure	• Nanofabrication facilities • High-performance computing for first-principles materials calculations • Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities		Foundry: Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities
Funding	Specific grants and funding programs targeting quantum technology and 2D materials research	FLAG SHIP	
Other	Establish interdisciplinary research teams with chemists, materials scientists quantum physicists and engineers		

Figure 15: Roadmap for Investigate and discover new qubit systems including 2D, topological and spintronics systems

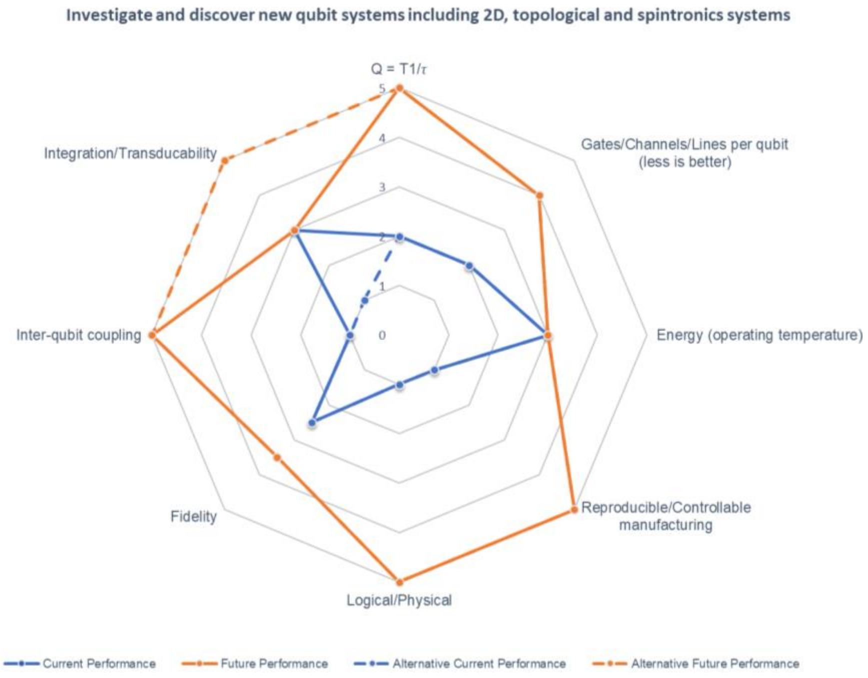

Figure 16: Current and future performance requirements for Investigate and discover new qubit systems including 2D, topological and spintronics systems (5 = excellent performance, 1 = poor performance)

Key enablers

Several enablers were identified as important for supporting the required developments in this technology area. These were categorised as skills and training, policies, infrastructure, and funding. These are discussed in the following sections.

Skills and Training

Several skills and training programs were needed to develop this technology area. Some of those were important for multiple material development critical in facilitating the growth of the quantum computing and communication technology area. These cross-cutting skills and training programs were the following:

- E2) Develop and provide community programmes, online resources, and EDI bursaries
- E3) Developing specialized educational programs at universities to train the next generation of researchers and engineers in quantum technologies and 2D materials e.g. packaging, materials characterisation, cryogenic characterisation of switches etc
- E4) Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements
- E7) Training and retaining PhD students
- E8) Supporting early career researchers. Early career researcher training/workshops in quantum sensing

These address both **attracting new researchers** into the field, **supporting, upskilling and/or continue to develop existing researchers** and **creating new educational and community programs** to train the next generation of researchers and engineers in quantum technologies.

The full list of skills and training enablers proposed is shown in the table below.

Table 5: Skills and Training enablers for the Quantum Computing and Communication technology area. The shaded areas indicate the most important enablers required by each of the priority topics.

	Low temperature electronics integration	Enable quantum transduction and frequency conversion for interconnecting qubits and QPUs	Characterisation of performance and routes to noise reduction and resilience including against correlated errors	Develop + Maintain characterisation tools for quantum platforms + metrology	Micro and Nanofabrication challenges of control and positioning for technologies on solid state	Efficient photonic integration of solid state quantum emitters	Investigate + Discover new qubit systems including 2D, topological + spintronics systems
E1) Dedicated CPD courses for high school teachers. Engagement in schools and beyond						■	
E2) Develop and provide community programmes, online resources, and EDI bursaries	■		■	■			
E3) Developing specialized educational programs at universities to train the next generation of researchers and engineers in quantum technologies and 2D materials e.g. Packaging, materials characterisation, cryogenic characterisation of switches etc.	■	■					
E4) Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements				■		■	
E5) Training for researchers to acquire skills in effective science communication, and outreach techniques						■	
E7) Training and retaining PhD students				■	■		
E8) Supporting early career researchers. Early career researcher training/workshops in quantum sensing			■	■			
E9) Supporting and encouraging more ambitious proposals orthogonal to the mainstream						■	
Fabrication photonics						■	
Classical control technology meets quantum (comms, RF, cryo. etc)		■					
Low temperature and higher spatial resolution microscopy and imaging				■			
Filtering: large scale filtering of electrical signals (fewer wires from RT, more control at low temperatures) and on-chip filtering	■						
Training in metrology and testing of devices		■					

Policy initiatives

Several policy interventions are required to support the further development of Quantum Computing and Communications in the UK. The cross-cutting policy initiatives that will positively impact several of the proposed material developments were the following:

- E10) Integrated national skills program including quantum technology spanning all educational stages and retraining. To incorporate skills such as physics, chemistry, chemical physics, computational modelling, and engineering. Also training specialised technicians
- E11) Government-led development of mission-led roadmaps for quantum impact, spanning fundamental research, development, and innovation
- E12) Policy for international partnerships to draw in critical capabilities and build supply chain opportunities
- E14) International Partnerships and Collaboration especially for fabrication facilities for all of the potential hardware platforms
- E15) Visa changes to allow new postdocs to move to the UK
- E16) Financial support and incentives for local quantum-related industries (policy, tax, tariffs, etc.)

Policy can play an important role to help **co-ordinate the activities at a national level** (both for skills development, and focus areas), establish **international partnerships** and **access to fabrication facilities**, **attract international talent** and **support the budding UK industry**.

The full list of policy initiatives proposed is shown in the table below.

Table 6: Policy initiatives for the Quantum Computing and Communication technology area. The shaded areas indicate the most important enablers required by each of the priority topics.

	Low temperature electronics integration	Enable quantum transduction and frequency conversion for interconnecting qubits and QPUs	Characterisation of performance and routes to noise reduction and resilience including against correlated errors	Develop + Maintain characterisation tools for quantum platforms + metrology	Micro and Nanofabrication challenges of control and positioning for technologies on solid state	Efficient photonic integration of solid state quantum emitters	Investigate + Discover new qubit systems including 2D, topological + spintronics systems
E10) Integrated national skills program including quantum technology spanning all educational stages and retraining. To incorporate skills such as physics, chemistry, chemical physics, computational modelling, and engineering. Also training specialised technicians							
E11) Government-led development of mission-led roadmaps for quantum impact, spanning fundamental research, development, and innovation							
E12) Policy for international partnerships to draw in critical capabilities and build supply chain opportunities							

E13) Broad-based and strategic approach to communications with tailored messages to inspire involvement in the quantum sector							
E14) International Partnerships and Collaboration especially for fabrication facilities for all of the potential hardware platforms							
E15) Visa changes to allow new postdocs to move to the UK							
E16) Financial support and incentives for local quantum-related industries (policy, tax, tariffs, etc.)							
Isotopically pure material held by other countries - build up national reserves							
Standardisation (e.g., of underlying qubit technology, qubit frequency/choice)							
Make the most of current opportunities							
Framing/pitching, brand as "UK based"							

Infrastructure requirements

Infrastructure is critical in this area to enable researchers and companies develop, test and scale-up promising materials, systems and architectures. Although some infrastructure maybe specific to the technology or platform chosen, there are some common requirements across the different material developments prioritised as part of this work. The common infrastructure proposed was the following:

- E17) Modelling of new materials and devices
- E18) High-performance computing for first-principles materials calculations
- E20) Pilot production facilities to bridge the gap between laboratory-scale research and industrial-scale manufacturing
- E22) Nanofabrication facilities
- E24) Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities
- Foundries and foundry cleanrooms

These range from **modelling** and **high-performance computing** to **nanofabrication facilities, pilot production facilities and open foundries** to enable industrial-scale manufacturing in the UK. It also includes a range of necessary **imaging, spectroscopy, and analysis techniques** necessary for the discovery, characterisation and performance evaluation of different concepts and systems. Some of these facilities may already exist in the UK, some maybe need to be improved and some will need to be developed to ensure the UK continues to be in the forefront of technological innovation.

The full list of infrastructure proposed is shown in the table below.

Table 7: Infrastructure requirements for the Quantum Computing and Communication technology area. The shaded areas indicate the most important enablers required by each of the priority topics.

	Low temperature electronics integration	Enable quantum transduction and frequency conversion for interconnecting qubits and QPUs	Characterisation of performance and routes to noise resilience including against correlated errors	Develop + Maintain characterisation tools for quantum platforms + metrology	Micro and Nanofabrication challenges of control and positioning for technologies on solid state	Efficient photonic integration of solid state quantum emitters	Investigate + Discover new qubit systems including 2D, topological + spintronics systems
E17) Modelling of new materials and devices					■	■	
E18) High-performance computing for first-principles materials calculations			■				■
E20) Pilot production facilities to bridge the gap between laboratory-scale research and industrial-scale manufacturing					■	■	
E21) Infrastructure for large-scale manufacturing of 2D materials and quantum device fabrication (fast waveguide switches, high efficiency single-photon detectors) and wafer scale testing						■	
E22) Nanofabrication facilities		■			■	■	■
E23) A UK-based facility for high-quality, thin overgrowth on diamond would enable bottom-up fabrication rather than always relying on top-down of commercial samples, or international collaborations					■		
E24) Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities				■		■	■
Cooling power of cryogenics	■						
National quantum facilities (including National Quantum Computing Centre, virtual)				■			
Access: XFEL, ARPES, DIAMOND, ISIS, REUDI				■			
Translation to low noise environment BOULBY				■			
M-optical assembly infrastructure						■	
Foundries and foundry cleanrooms						■	■

Versatile multinational lab for prototyping hybrid devices							
Control RF electronics							
Cryostats in required I/Os and mechanical stability DP closed-cycle dilution refrigerators							
Dark fibre network access							

Funding and Collaboration Enablers

Adequate and long-term funding is essential in order to develop this technology area and remain competitive. Interdisciplinary collaborations are also critical as the UK will not have sufficiency in skills and infrastructure. The most commonly mentioned funding areas and collaboration opportunities were the following:

- E26) Funding to employ senior research associates in national facilities able to produce service work and ensure continuity of equipment. A higher level of senior researcher involvement is needed in the growth and processing of materials
- E27) Adequate funding from various bodies in research grants to support long-term research projects
- E28) Specific grants and funding programs targeting quantum technology and 2D materials research
- Equipment funding (EPSRC/UKRI strategic equipment for single lab systems, flexible funding schemes for capital equipment (up to £700k, for example a Dilution fridge cost is ~£500k, for demos)
- E29) Establishing collaborative networks in academia with input from industry and research institutions to foster knowledge exchange and interdisciplinary research.
- E30) Establish interdisciplinary research teams with chemists, materials scientists quantum physicists and engineers

The funding needed was for **recruitment of experienced personnel**, **research projects**, and **equipment**. **Interdisciplinary collaborations** between different specialities, including industry and academia are also important for progressing in this field.

The full list of funding and collaboration enablers proposed is shown in the table below.

Table 8: Funding and Collaboration enablers for the Quantum Computing and Communication technology area. The shaded areas indicate the most important enablers required by each of the priority topics.

	Low temperature electronics integration	Enable quantum transduction and frequency conversion for interconnecting qubits and QPUs	Characterisation of performance and routes to noise resilience including against correlated errors	Develop + Maintain characterisation tools for quantum platforms + metrology	Micro and Nanofabrication challenges of control and positioning for technologies on solid state	Efficient photonic integration of solid state quantum emitters	Investigate + Discover new qubit systems including 2D, topological + spintronics systems
E26) Funding to employ senior research associates in national facilities able to produce service work and ensure continuity of equipment. A higher level of senior researcher involvement is needed in the growth and processing of materials				■	■		
E27) Adequate funding from various bodies in research grants to support long-term research projects				■	■	■	
E28) Specific grants and funding programs targeting quantum technology and 2D materials research						■	■
International funding					■		
Purchase of CMOS multiplexing (work with manufacturers)	■						
Alternative materials to HEMTs (Hub, EPSRC)	■						
New materials to CMOS - RSFQ, Research Programmes (Hub, EPSRC)	■						
NPL/UKRJ - standards	■						
Equipment funding (EPSRC/UKRI strategic equipment for single lab systems, flexible funding schemes for capital equipment (up to £400k), (fridge + RF equipment) for demos)		■	■	■			
Funding for national/virtual national facilities building on existing capabilities				■			
Prosperity partnerships with start-ups			■				
Target discipline hopping for electrical engineers to work in quantum			■				
Investment in new materials and systems early! (Feeds into missions)		■					
Government procurement of prototypes		■					
E29) Establishing collaborative networks in academia with input from industry and research institutions to foster knowledge exchange and interdisciplinary research.				■		■	
E30) Establish interdisciplinary research teams with chemists, materials scientists quantum physicists and engineers				■		■	■

Sensing and Imaging

KEY OUTPUTS

Background

Quantum sensing enables significantly enhanced precision compared to classical sensors by taking advantage of the inherent sensitivity of quantum states of particles, which act as measurement probes, to changes in environment[23].

Quantum sensors can be used to quantify physical properties like acceleration and gravity, magnetic and electric fields, rotation, and the passage of time. That opens a range of possible industry applications, including faster and more reliable geolocation, enhanced information for medical diagnosis, navigation and guidance systems for autonomous vehicles and aerospace applications, and many others[24].

Quantum imaging leverages entanglement and superposition, to devise novel techniques for optical imagining with sensitivity and resolution beyond capabilities of classical optics. The most mature quantum imaging protocols include ghost imaging, sub-shot noise imaging, quantum illumination and sub-Rayleigh imaging[25]. Quantum imaging offers advancement across multiple sectors, including medical diagnostics, surveillance, environmental monitoring and many more. However, to fully realise these opportunities, several challenges must be first overcome.

Key challenges

Overall, 36 challenges were identified through desk research and participants' input pre-workshop relating to sensing and imaging applications. During the workshop the participants reviewed and edited the list. Participants have voted on the importance of challenges in order to identify the challenges that should be priorities. The results led to the identification of fifteen key challenges shown in the table below.

Table 9: Consolidated list of challenges relating to sensing and imaging applications, reviewed, and prioritised by participants in the workshop.

	Challenge
A	Electrical readout and manipulation of quantum states; controllable coupling of individual solid-state; Integration of quantum emitters with photonic networks for efficient coupling; building devices with tailored capabilities for specific sensing applications e.g., nano-NMR; high-yield assembly of molecular devices; design molecules for devices rather than devices around molecules (architecture)[10, 12, 15]
B	Developing characterisation tools for quantum platforms e.g., calibration in vivo, internal strain, and environmental variables affecting sensor effectiveness; nanoscale spectroscopic characterisation at low temperature; in-situ materials characterisation interfaces, operation under vacuum[15,26, 27]
C	Micro and Nanofabrication Challenges e.g., precise positioning of Colour Centres for technologies based on colour-centres in diamond including purity control, defect characterisation, surface quality management, and functionalization for enhanced quantum sensing[10,16]
D	Sustainability - materials, processes, devices, operation; Consideration of energy and resource investment in tech development

[23] https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.89.035002
[24] https://www.cambridgeconsultants.com/insights/opinion/what-is-quantum-sensing
[25] https://iopscience.iop.org/article/10.1088/2040-8978/18/7/073002
[26] https://epjquantumtechnology.springeropen.com/articles/10.1140/epjqt/s40507-021-00113-y
[27] https://www.sciencedirect.com/science/article/pii/S2772949423000438

E	Integration of quantum materials into robust packaging for real-world systems; micro -& nano fab for all materials –precise[27]
F	Integration of quantum emitters with photonic networks for efficient coupling; on-chip QD based photonic sources desired QD state, high brightness site control[10]
G	Integration challenges (scalability/robustness). Inhomogeneity of poorly controlled/characterised materials/interfaces/devices[17]
H	Engaging and inspiring communication/outreach; Facilitate interaction for 'pull' from industry and end users (e.g., clinicians)
I	Identifying and growing improved bulk crystals with reduced nuclear spin concentration and ultra-low rare-earth background impurities in Rare-earth ions systems. identifying and growing high-purity materials with controllable nuclear spin concentration and ultra-low background impurities[12]
J	Structure function prediction for spin-based quantum sensing
K	Challenges with decoherence, short coherence times and dephasing by addressing hyperfine interactions, environmental impacts, and charge trap effects in various quantum systems[10, 14, 28]
L	Material quality challenges e.g., inhomogeneity of poorly controlled/characterised materials/interfaces/devices
M	Optical routing in waveguides, active modulation and switching at blue and ultraviolet wavelengths in Trapped ions systems[11]
N	Challenges in fabrication methods and the need for large high-quality materials for practical deployment of 2D quantum platforms including monolayer fabrication, entanglement, and superconductivity in SPEs, carrier recombination, and maintaining coherence in upscaled systems[12, 17, 28]
O	Miniaturization of optical sources, detectors, and components, and quantum RF antennas[10, 26]

Full list of challenges reviewed by participants is available in Appendix 5.

[28] https://onlinelibrary.wiley.com/doi/10.1002/adma.202109621

Material developments required to address key challenges

Overall, 37 potential material developments were identified via participant input and literature review. These were subdivided into the four major sub-categories:

- Material discovery
- Modification of existing materials
- Materials integration
- Other

Table 11 (below) shows the number of material developments included within each sub-category.

Table 10: Number of material developments identified per sub-category

Subcategory	Number of material developments proposed
Material discovery	6
Modify existing materials	11
Materials integration	9
Other	11

The list was reviewed and refined further during the workshop. The refined lit was assessed using two different and broadly separate considerations: impact and feasibility. Impact was defined as the magnitude of the opportunity plausibly available. Feasibility was defined as how well prepared the sector is to grasp the opportunity.

The impact and feasibility criteria had been selected prior to the workshop by the M4QN steering Committee. The ones selected and used during the workshop are shown in Figure 17 (below).

Impact	Feasibility
1. Potential for the technology to be scaled	1. Future cost of technology when is scaled
2. Increasing UK resilience i.e. addresses existing gaps	2. Ability for the technology to securely interface with other supporting technologies

Figure 17: Impact and feasibility criteria used to assess the different material developments needed for quantum sensing and imaging applications

The assessment process took place in two parts. First, each participant was asked to review the reviewed material developments list and independently select 8 using sticky dots, based on the impact factors. This created a shortlist of material developments.

In the second step, participants were asked to consider only material developments that had already received impact votes. Each participant was then asked to independently select four material developments based on the feasibility factors. The second prioritisation step narrowed the material developments down to a shorter list of 13, which was considered further during the workshop. This shorter list still contained material developments from all sub-layers of the roadmap and across all different timescales.

The prioritised list of material developments is shown in Figure 18 below. The full list of material developments and their votes is shown in Appendix 7.

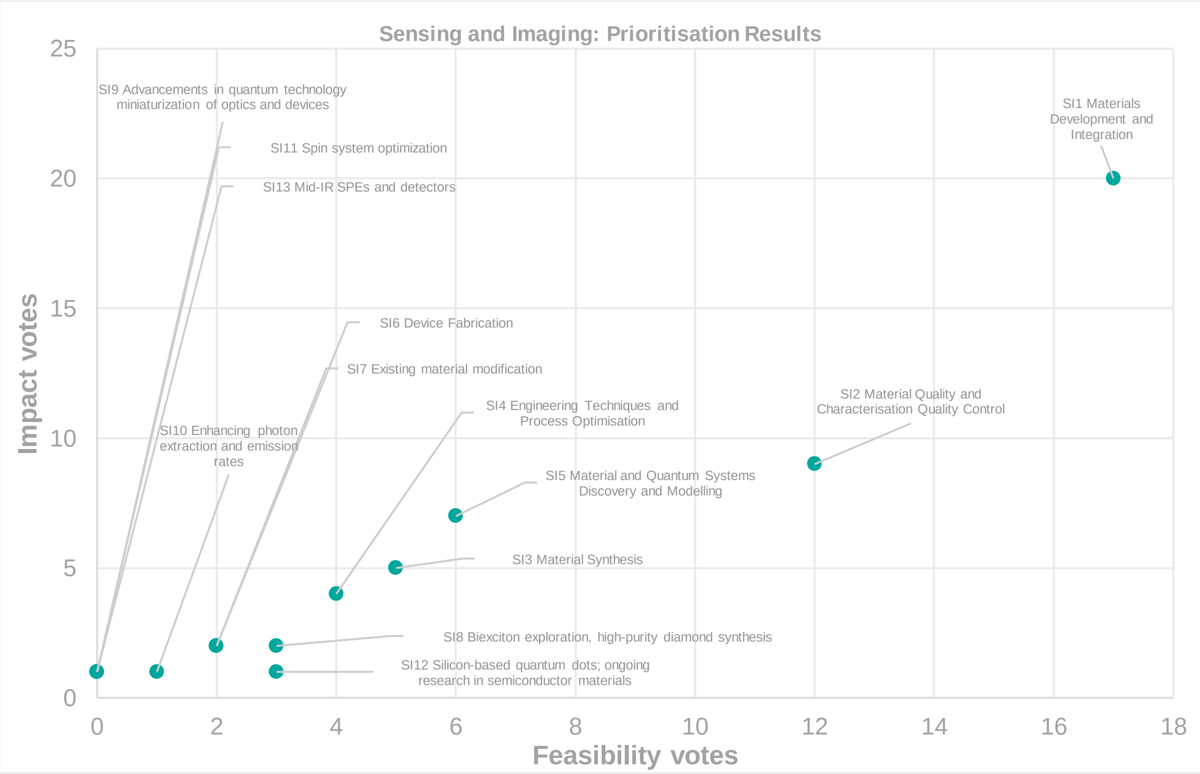

Figure 18: Prioritised material developments related for sensing and imaging quantum applications using Impact/Feasibility criteria

The following six key material development areas were created for further exploration in smaller groups, as the result of high impact/feasibility score and clustering based on content similarities:

1. **Materials Development and Integration -** Multifaceted material integration including heterojunctions, nanophotonic device fabrication, and precise interfacing techniques; Development of materials towards on-chip photonic systems, e.g., integration of source/transmitter and receiver/detector; Ultra low-loss optical materials for quantum photonic integrated circuits; Developing new materials for non-linear optics in quantum photonics.[12 27]

2. **Material Quality and Characterisation Quality Control -** Material Quality and characterisation quality control: Quality control in defect materials e.g., SiC, Diamond, etc.; Tailoring doping, isotopic composition, purity, with resilient UK supply; Material quality and characterisation including trap density management, defect control, nano-atomic characterisation, and polycrystalline structure understanding.

3. **Material Synthesis -** Establishing control over inter-molecular structured interactions (e.g., by synth-DNA conjugation); Atomically precise material synthesis at scale.

4. **Engineering Techniques and Process Optimisation -** Advanced photonic material engineering including GaP metasurfaces, SPE integration, defect exploration in hBN and TMDs, and quantum emitter optimization for high-efficiency applications of single-photon emitters (Including layered materials (LBN,TMD) for photonic applications).[10 17 28]

5. **Material and Quantum Systems Discovery and Modelling -** Exploring alternative growth techniques like MBE and PEALD; research on materials with higher critical temperatures; High quality thin film materials; Automated discovery and characterisation of spin systems in different materials with optimal measurements; Material discovery and formulation innovation.[12]

6. **Device Fabrication -** Device fabrication platform for EBL, Dry etching etc. like material beam etc. and National Epitaxy Facility; Expand nano-fab, e.g., flip chip lithography for hybrid devices.

Those and the challenges that they address were explored further in small groups. The full linking grid of challenges and material development areas that addressed them is shown in Appendix 6. Each group discussed and developed a roadmap to address a material development topic. The roadmap included the following fields:

- Scope and boundaries of the application, indicating aspects that are included and excluded from further development;
- Figures of Merit that need to be achieved;
- Required materials and other enabling technologies;
- Any key enablers such as skills and training, policies, infrastructure and funding.

The current and future Figures of Merit (FoM) needed to guide each material development were also summarised. These were assessed using a linear Likert scale from (1) to (5), where (1) indicates poor performance and (5) indicates excellent performance. The FoMs were derived separately for each material development. Some FoM discussed in the literature were presented to all participants for consideration and inclusion to the discussions if appropriate.

Some FoMs were common across challenges and material developments. These were emission and collection efficiency of emitters (coherence), Operating temperature, conversion efficiency; Uniformity/Reproducibility/ Manufacturability/Yield, Scalability (for individual devices). Three of those (emission and collection efficiency of emitters (coherence), Operating temperature, and Uniformity/Reproducibility/ Manufacturability/Yield are important across multiple material developments and should be addressed as a priority by putting in place specific research and technology development activities.

Table 12 (below) shows the five common Figures of Merit, their applicability for each of the material developments, as well as the current performance gap (i.e., 0 = no performance gap, 4 = maximum performance gap).

Table 11: The five common performance parameters across the six material developments. The numbers indicate the current performance gap (i.e., 0 = no performance gap, 4 = maximum performance gap)

Material development / FoM	Materials Development and Integration	Material Quality and Characterisation Quality Control	Material Synthesis	Engineering Techniques and Process Optimisation	Material and Quantum Systems Discovery and Modelling	Device Fabrication
Emission and collection efficiency of emitters-coherence; Coherence time/ Quantum Phenomena; Indistinguishability /Coherence	1.5		0	2		
Operating temperature (inter-operability of all components); Operating Temperature;	2		2	4		2
Routing and manipulations of photons, optical loss, maintaining coherence, non-linear conversion efficiency; Conversion efficiency	2					2
Uniformity/Reproducibility/ Manufacturability/Yield; Suitable characteristics techniques hardware & data methods, Robustness and reproductivity, Applicability wide range of materials and applications; In SITU/operando Reproducibility	3	2	2			1
Scalability (for individual devices)			2	2.5		

Topic 1: Material Development and Integration

Definition and scope

This topic addresses the challenge of synthesising, fabricating, scaling-up and integrating different materials with photonic components and photonic integrated circuits.

Current challenges

Synthesis, fabrication, and then scale-up methods are the key challenges of integrated quantum photonics. Whereas integrated photonics is a well-established industry in telecoms, for quantum applications there is still a lot of work that is required. Alongside materials, there is also the need for processes to address *quantum* integrated photonics.

There are a range of different options: each of them has different levels of maturity and materials challenges that need to be addressed. The common challenge is to get these different materials to work together. The key challenge for quantum technologies in particular, is maintaining coherence. A lot of these materials can be used to make classical integrated photonic circuits to carry out many telecom operations. However, when quantum technologies are incorporated into classical integrated photonic circuits, the interfaces and interactions between the different materials affect coherence. Therefore, it is vital to utilise materials that will work together. Other important parameters are synthesis methods and the fabrication processes, and the scaling of processes to build fully integrated working systems. There a range of features that need to be developed across the materials, ability to synthesise the materials, particularly improved active materials efficiency, reducing losses and development of a materials platform approach to integration and scale-up.

Such developments will cut across the range of materials. For example, in semiconductors, semiconductor quantum dots and semiconductor detectors have already achieved levels of maturity that have demonstrated quantum functionality such as entanglement and teleportation of photons. But they have significant challenges in terms of light extraction efficiency, extending wavelengths and maintaining coherence, especially when they are integrated with other materials.

There is a range of 2D materials and molecular materials. These are still under development and have been used only for basic demonstrations of, for example, single photon sources, but they need to develop further to demonstrate advanced quantum properties including entangled photon sources and to improve synthesis and fabrication methods, especially at scale and with high yield and uniformity. The immediate goals are to address those challenges and establish feasibility for families of materials. Although some of the materials showed promise, they need to be integrated into quantum systems in order to be developed further and this will inevitably eliminate some of those material choices meaning some of them will stop there. A key feature of the selection of materials process beyond those that display desirable properties, is to identify those that demonstrate compatibility with key integration platforms (for example silicon photonics, GaN photonics, SiN photonic platforms etc.)

Development of new synthesis methods is a particularly pressing need for the enabling technologies. An example is 2D materials, where the best materials are still made by flake-based processes. Larger area processes will need to be established in order for these materials to be developed further. Additional needs are fabrication methods that do not destroy basic quantum properties such as coherence. In the semiconductor industry researchers have acquired 50 years of very high-quality fabrication processes for lasers and everything that makes the modern world work. But many of these processes can degrade or destroy coherence and must be improved to make them viable for quantum applications.

Key figures of Merit

Several key Figures of Merit were identified, for both the quantum state and the overall system integration. These were as follows: emission and collection efficiency of emitters-coherence, routing and manipulations of photons, optical loss, maintaining coherence, non-linear conversion efficiency spectral range-emitters, detectors and waveguides, detection efficiency of detectors (for integrated detectors), operating temperature (inter-operability of all components), quantum-state readout efficiency, integrability/compatibility (interfacing integrity), uniformity/reproducibility/manufacturability/yield and finally reliability.

Key enablers

Several enablers are required in this area, many around skills development for undergraduates, doctoral students and early career researchers. Establishing international collaborations and networks is also critical as well as working within multidisciplinary research teams that combine basic and applied research. Specific infrastructure is also required for both research but also scale-up manufacturing.

Figures 19 and 20 (below) show the roadmap and the current and future performance requirements to address this challenge.

Materials Development and Integration		**What's IN Scope:** Multifaceted material integration including heterojunctions, nanophotonic device fabrication, and precise interfacing techniques; Development of materials towards on-chip photonic systems, e.g. integration of source/transmitter and receiver/detector; Ultra low-loss optical materials for quantum photonic integrated circuits; Developing new materials for non-linear optics in quantum photonics. **What's OUT of Scope:** Basic material discovery Characterisation Novel architectures: - devices structures - components (individual designs)	**Desired future (key figures of merit):** Low optical loss Nonlinear conversion efficiency (maintain coherence) Increased spectral range(e.g., m.u IR,UV) emitters, detectors, waveguides, etc. Operating temperature teach integrated Interoperability Optical efficiency (maintaining coherence) Detection Emission & collection Non-linear Waveguiding Switching
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
2D materials		Synthesis/Fabrication and demonstration of single photon emission/detection in 2D materials Single-entangled photons (coherence) Integration processes	Full integration Multiple quantum properties optimisation (emission, detection, etc.)
Molecular material	Demonstrate basic quantum properties Synthesis Stability	Down selection of most promising materials	Interfaces and surfaces control
Semiconductor and photon	Improvement in efficiency (emitters & detectors) Start of scale-up Extending Spectral Range New compatible materials per low loss waveguide. Non-linear waveguide e.g., low loss Sic,LiNbO,GaN	Integration process and optimisation of materials for integration	Scale-up and manufacturability(yield, reproducible, uniformity, stability)
Solid state defects	Material supply especially Diamond SiC	Scale-up potential esp. uniformity	
Spin and topology	Identify most promising systems for integration Design concepts and tools		
Superconductor	Higher temperature superconducting detectors for integration		
Other	Interfacing/integration/compatibility, generic challenges		
Enabling Technologies	Synthesis methods Fabrication methods (maintaining coherence), reducing noise (detectors)	Scale-up processes	
Skills and Training	• Developing specialized educational programs at universities to train the next generation of researchers and engineers in quantum technologies and 2D materials e.g. Packaging, materials characterisation, cryogenic characterisation of switches etc. • Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements • Training for researchers to acquire skills in effective science communication, and outreach techniques • Encourage collaborating with artists specialising in visual arts, music, performance, or other creative disciplines, in order for innovative avenues for communicating complex concepts to be opened • Training and retaining PhD students • Supporting early career researchers. Early career researcher training/workshops in quantum sensing • Visa changes to allow new postdocs to move to the UK • Cleanroom skills		
Policies	• Policy for international partnerships to draw in critical capabilities and build supply chain opportunities • Visa changes to allow new postdocs to move to the UK cleanroom skills		
Infrastructure		• Specific fabrication facilities for heterogeneous integration diverse materials • Synthesis and fabrication processes at scale (industrialisation, foundries) • Small scale state-of-the-art laboratories equipped with advanced tools for the synthesis, characterization, and testing of 2D materials. High purity material growth facilities e.g. MBE, MOVPE, MOCVD for host material synthesis. Controlled defect generation. Dedicated material growth facilities. • Have a UK source of Diamond material (synthesis/growth) rather than always relying on top-down of commercial samples, or international collaborations.	
Funding	• Establishing collaborative networks in academia with input from industry and research institutions to foster knowledge exchange and interdisciplinary research • Establish interdisciplinary research teams with chemists, material scientists quantum physicists and engineers		

Figure 19: Roadmap for Materials Development and Integration

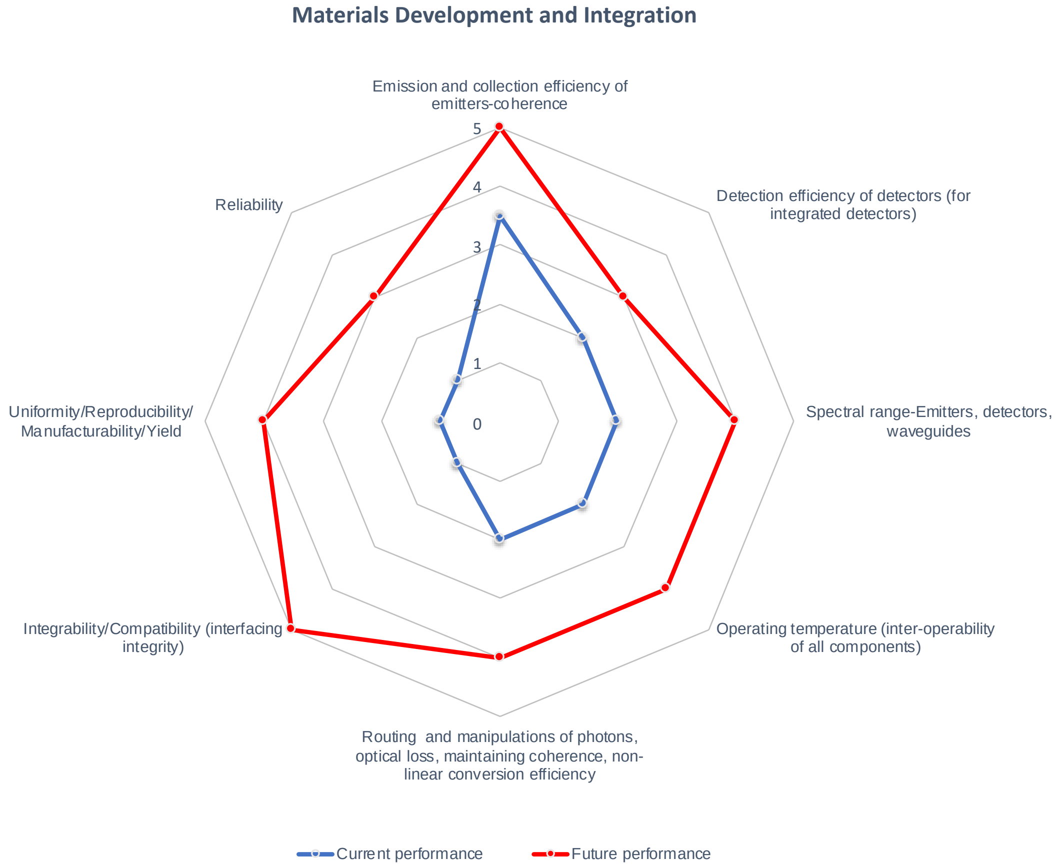

Figure 20: Current and future performance requirements for Materials Development and Integration (5 = excellent performance, 1 = poor performance)

Further details on future improvements that are necessary to achieve desire final performance for this area, are shown in Table 16 (below).

Table 12: Further details on improvement measures for specific Figures of Merit achieving the desired final performance for Material Development and Integration

	Current	Future (10 years)
Emission and collection efficiency of emitters-coherence	Most advanced are QDs, followed by Diamond. All have remaining challenges which depend strongly on the overall integration scheme.	Scale-up target
Detection efficiency of detectors	SNSPDs - λ, T	SPADS
Routing and manipulations of photons, optical loss, maintaining coherence, non-linear conversion efficiency	Various demonstrations on several platforms but all have ongoing significant challenges in terms of materials properties such as losses, synthesis etc. No clear 'winners' yet that show full commercial viability in the long run.	λ, T improvements Multiple materials development needs. Need for clear design methodology and conceptual ideas for quantum functionality to be closely aligned with ongoing materials development needs

Topic 2: Material Quality and Characterisation Quality Control

Definition and scope

Material quality characterisation although a very classical field, poses additional challenges for quantum applications. For example, quantum technologies can require several-orders-of-magnitude higher levels of sensitivity to material parameters than required for classical applications.

Current challenges

Presently there are different material systems that are explored by the research community that have different Figures of Merit and therefore quality control requirements. These will need to be agreed by the community, so suitable methods and protocols can be developed and employed. The different Figures of Merit, and corresponding measurement methods should be validated through inter-lab studies and quality control test beds and demonstrators.

Furthermore, industry and/or national standards development are an important pre-requisite to representing UK interests in international standards development activities.

Key figures of Merit

Key Figures of Merit are those that describe the material quality at the basic material level, however it is also accepted that the material properties should be related to specific applications. There is also the need to develop suitable characterisation techniques for material quality control. Such techniques do not yet exist, or have not been applied to new materials and new applications. ,They need to be robust, reproducible and applicable to a wide range of materials. The methods must also be easy to use with careful attention paid to throughput and scalability to support scale-up of materials and technologies into industry use. Users will also require reference data, reference materials, documentary standards and standard operating procedures for all of the measurements.

In order to achieve the aforementioned goals over the ten-year timescale there needs to be a common agreement and understanding within the research and industrial communities on the figures of merit. In the first year or first few years, it is recommended to carry out a survey to understand the figures of merit and needs, for all of the different materials and applications of interest. These should be listed and prioritised in the order in which they are to be addressed. Research efforts should be led by those figures are merit - in terms of developing processes, and in the different kinds of measurements that might be needed in order to do that. For example, electrical, optical, and noise measurements, data standards and the need for multi-modal, multi-scale measurement infrastructure.

Key enablers

Skills are another important issue. There are several concerns regarding the quality control of specific materials, the security of supply for critical materials, but also critical suppliers. A short-term priority would be to establish an international cooperation to discuss the needs around ITAR restrictions and hostile nations.

Figures 21 and 22 (below) show the roadmap and the current and future performance requirements to address this challenge.

Material Quality and Characterisation Quality Control		Measurement simulation Developing metrics Developing techniques &SOPs Material Optimisation Developing standards **What's OUT of Scope:** Material discovery & synthesis Material modelling	Defect, defect density, scalability, purity Application FOMs: optical/electric/thermal/magnetic p Robust definition of FOMs and measurement SOPs
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
2D materials	Agree FoM		
Molecular material		Agree FOMs for molecular material	
Semiconductor and photon			
Solid state defects	Agree FoM		
Spin and topology			
Superconductor			
Other	Survey of needs to cover full range of materials and applications	Industry/national standards development Validation of FoMs through inter-lab studies Quality control test beds/demonstrators	Agree FOMs for novel materials International standard process
Enabling Technologies	• Quantitative localised states measurement • Reference material data & Calibration samples • High sensitive techniques for low defect densities • SOPs for optical spectroscopy • Noise measurement at quantum limit • Data standard & analysis	• Non contact electrical measurement for high sensitivity and throughput • Sensitive surface analysis for low defect densities • User - friendly automated measurement & analysis • Electrical detector for single electrons • Multimodal measurement methodologies	
Skills and Training	• Retraining and re-skilling initiating + CPD • Metrology training uncertainity & instrumentation • Quantum graduate training • Short conversion course	Data skills Apprenticeships & technician training	
Policies	• Joined up with other policies • Open source data policy • Recruitment and retention • Visas	• Government procurement policy and support quantum & industry • Support for early adoption & increase demand	
Infrastructure	• Supply chain for critical material ITAR & hostile nations expert capability • International collaboration • Infrastructure for validation & cross-method comparison	Access to centralised tools and characterisation	
Funding	• Higher salaries • Support for international collaboration • Funding include interlab companies	Support for instrument manufacturing industry	

Figure 21: Roadmap for Material Quality and Characterisation Quality Control

Figure 22: Current and future performance requirements for Material Quality and Characterisation Quality Control (5 = excellent performance, 1 = poor performance)

The intermediate targets for achieving the desired final performance are shown in the table below.

Table 13: Intermediate targets for achieving the desired final performance for Material Quality and Characterisation Quality Control

	Current	10 years
Robustness and reproducibility	No agreed FoMs in most cases so comparisons not possible.	Agreed FoMs for material parameters and accurate measurement methods available with traceability to the SI
Throughput	Research tools are slow and suitable for measurements of individual samples with micrometre-scale filed of view.	Wafer-scale instruments commercially available for high-throughput measurements of all relevant material quality FoMs.
Reference data and materials	Manufacturers and labs have own references that are not shared.	Reference materials available for all relevant materials, and reference data available through open repositories.
SOPs	Good practices emerging in research labs but no consensus standards have been developed.	Measurement and test consensus standards published describing accurate measurement of material quality FoMs

Topic 3: Material Synthesis

Definition and scope

Included in the scope of this topic were material ideas that have been generated from the bottom-up, i.e. developed at the smaller scale over which the design of a desired quantum property or function can be developed and controlled. Out-of-scope for this topic was materials where quantum phenomena were engineered top-down. The focus therefore is on a sub-ten nanometre regime and systems using chemical synthesis.

Current challenges

A challenge in this area is to ensure that organic materials and molecular materials can tangibly demonstrate a capability that is ready to be used for a quantum system. Proof-of principle quantum sensing demonstrations are attractive near-term targets. Broadly, molecular materials are defined by their scale and the modifications happen at the atomic or the small chemical group level.

When the device is lowered at the molecular scale, experiments can be conducted with the molecules themselves, similarly to the pharmaceutical industry. This is also potentially a scalable process. A pivotal component of this is the question about how to do integration and scale of molecular components. Changes are happening in the technology of assembly at the molecular scale. The landscape of synthetic biology in particular, is shifting. This field of research is highly interdisciplinary, and a challenge/opportunity is for increased collaboration across communities spanning chemistry, physics, materials science, and computation.

Key figures of Merit

The key figures of merit are operating temperature, size and scalability; the number of active quantum components that can be integrated into a device, integrability with other systems, yield and reproducibility of quantum capability, sensitivity to different physical quantities for quantum sensing, and coherence time.

Key enablers

Apart of the material synthesis requirements, several enabling technologies are also needed in order to achieve better synthesis capabilities at scale as well as development of modelling, multi-scale modelling and ab initio modelling. Another important aspect is the integration between molecular quantum components and molecular or structural components to drive an increased yield. Overall, there needs to be better control defect engineering, particularly for 2D materials. The ultimate goal is to modularize molecular assembly or 2D assembly to try and improve scalability and yields.

In terms of policy and funding, this is essential to bring chemistry into the quantum technology conversation and quantum strategy. Collaboration opportunities with chemist should enable better molecular designs and better understanding and characterisation of surface chemistry, and provide a rich parameter space to explore. The goal is therefore to organise multi-disciplinary workshops and funding and lab exchanges that bridge disciplines. For this, resources are needed to devise a programme grant hub scheme in which researchers can explore some of these properties to better appreciate the diverse capabilities, particularly in the UK.

One particular policy activity could be to examine the international collaboration landscape, which currently focuses on high TRL areas in which collaborations can be established with UK institutions, particularly in areas like superconducting qubits. Researchers could also try and bring in some of the lower TRL opportunities that are not burdened by significant barriers to international knowledge exchange or export controls because they are lower TRL. Another suggestion is for policy to focus in the short term on round tables and two-way education and engagement with end-user and investment communities so they understand what quantum technology can do for them and they can tell the research side what they need from a future technology in sensing or in imaging. Mid to long-term, engaging with end-user and investment communities will be important so that they are informed about the different design processes.

Regarding skills and training the short-term focus should be on materials and quantum characterisation synthesis, device design and nano fabrication. The medium to long term focus should be on quantum control, cryo-measurements and RF circuitry.

Figures 23 and 24 (below) show the roadmap and the current and future performance requirements to address this challenge.

Material Synthesis		Establishing control over inter-molecular structured interactions (e.g. by synth-DNA conjugation); Atomically precise material synthesis at scale. **What's OUT of Scope:** • (<10nm) smallest scale where you can design quantum function • Challenges with decoherence, short coherence times and dephasing by addressing hyperfine interactions, environmental impacts, and charge trap effects in various quantum systems • Material where quantum phenomena can be engineered TOP DOWN	(HIGH) YIELD and REPRODUCIBILITY of quantum coherence time SCALABILITY how many active quantum component integrated into device Size Operating Temperature
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
2D materials	Optimising single and multi-layer large area 2D materials	Reproducible high yield single molecule devices	Complex integrated devices inc molecules and 2D ma
Molecular material	Initiation and read out of molecular quantum states Few nm-100s nm molecular to meso-scale bridge	Operating temp understanding spin phonon interactions, modelling, exploring (organic) chemistry parameter space	
Solid state defects	Understanding and engineering defects, strain etc		
Other	Survey of needs to cover full range of materials and applications	Industry/national standards development Validation of FoMs through inter-lab studies Quality control test beds/demonstrators	Reproducible High sensibility High SNR Operate at RT
Enabling Technologies	Preservation of quantum properties in operando/in complex environment Chemical synthesis at scale Modelling (ab initio, multi-scale etc) Integration between molecular quantum component & (molecular) structure components --> will increase yield	Controlled defect engineering --> (2D) scalability MODULARISING MOLECULAR ASSEMBLY --> WILL IMPROVE SCALABILITY	
Skills and Training	quantum chemistry device design/nanofab materials & quantum characterisation materials synthesis	Quantum control Cryo measurements RF Circuitry	UG courses on molecules quantum tech. & 2 D highly systems
Policies	• Visa changes to allow new postdocs to move to the UK • Training and retaining PhD students • Supporting early career researchers. Early career researcher training/workshops in quantum sensing • Low TRL investment & international collaboration • End user / investor education & round tables	• Technicians -->Hire, Support, Pay, Promote • Government-led development of mission-led roadmaps for quantum impact, spanning fundamental research, development, and innovation • End user / investor engagement	Molecular - focused quantum missions
Infrastructure	• Easily accessible, affordable and versatile nanofab • MOCVD / commercially available synthesis component		
Funding	• Interdisciplinary workshop, lab exchanges • Explicit mention of chemistry in quantum funding calls	• Atomically defined materials • Molecular quantum programme grant / quantum hub	
Other	Better appreciation of chemistry in National QT programme		

Figure 23: Roadmap for Material Synthesis

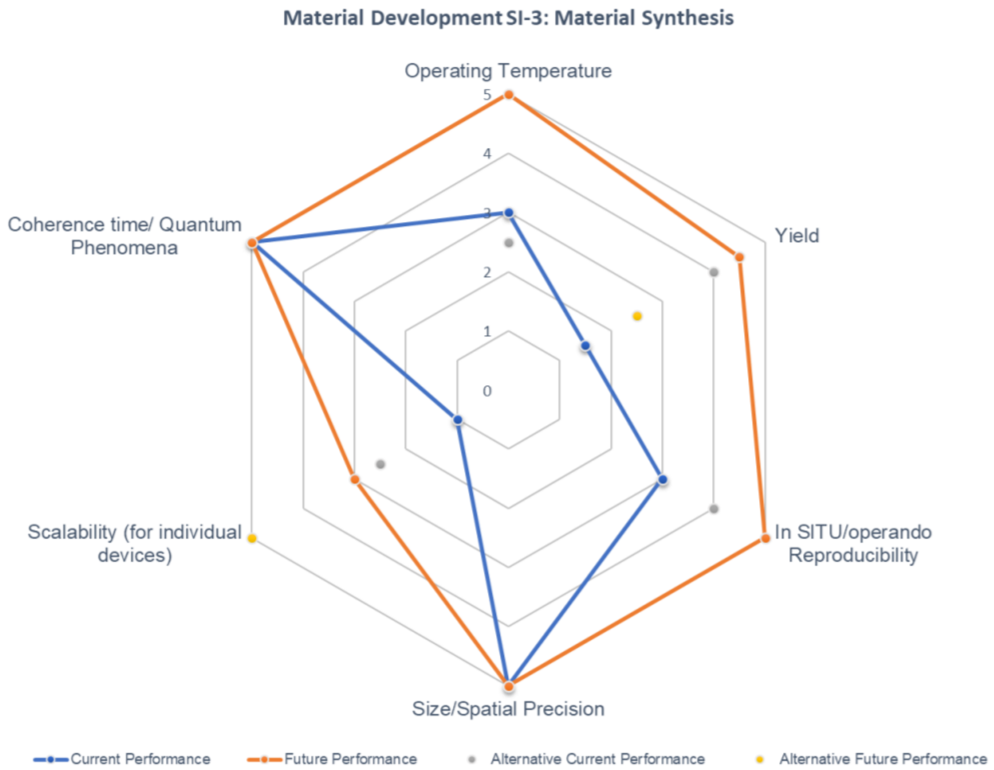

Figure 24: Current and future performance requirements for Material Synthesis (5 = excellent performance, 1 = poor performance)

Further details on current states and future improvements and corresponding targets that are necessary to achieve desire final performance for this area, are shown in Table 14 (below).

Table 14: Further detail on current states and necessary targets for improvement for achieving desired final performance for Material Synthesis

	Current	Future (10 years)
Operating Temperature	- Ensemble – Room Temp - Single-mol 2D material – 4K	Room-temperature coherent single-molecule systems
Yield	- Ensemble – Level 4 performance - Sub 1% – Level 1.5 performance	Single molecule devices=95% - level 4.5, multi molecular components devices - level 2.5
In SITU/operando Reproducibility	- Single molecular devices – Level 3 performance - Many molecular devices – Level 4 performance	100% Reproducibility of quantum properties
Scalability (for individual devices)	- Break junctions – Level 1 performance - Self-assembly methodologies (e.g., MOFs, DNA, etc) – Level 2 performance	- Break junctions – Level 3 performance - Self-assembly methodologies – Level 5 performance

Topic 4: Engineering Techniques and Process Optimisation

Definition and scope

This topic includes high-performance photon sources, particularly single photon emitters, quantum emitters and integration with nano-photonics. Selecting appropriate Figures of Merit for this topic is challenging as there are a range of materials at different maturity levels that can be used for a single emission, for example, III-V quantum dots are very advanced and currently close to the required performance for applications

Current challenges

Nevertheless, some key requirements for the technology development in this area are the purity of single photon emission, a generation rate with very high indistinguishability, coherence, and external quantum efficiency. The type of drive, i.e. electrical drive versus optical drive, as well as scalability are also important. Scalability in this context is defined as designing for a certain performance, measuring the real device performance and the subsequent yield. The aim is to achieve 50% of the defined performance. Currently, even the most mature technologies such as III-V quantum dots cannot achieve that. Much progress must be made in this area.

The wavelength required to enable coupling of the nanophotonic structures with any photonic circuitry is also a critical parameter. This requires fine tuning of the emitter wavelengths in resonance with the cavity mode or waveguide mode. Fine tuning is therefore essential to achieving target wavelengths, for various single photon emitters.

Finally, another important Figure of Merit is the temperature at which single photon emitters perform. Liquid nitrogen temperatures (77 Kelvin) should be the goal temperature, although cryogenic temperature such as liquid helium temperatures (4 Kelvin) may be suitable for future applications.

Key figures of Merit

There is good progress achieved so far for certain Figures of Merit and specific materials e.g. III-V quantum dots. However, further development is required to achieve the required scalability, reliable fabrication, and reliable integration in nano-photonics. Additional facilities are also needed. Ideally, these should be high-end semiconductor fab and clean rooms. Furthermore, although some technologies such as electron beam lithography are available at numerous universities, the downtime can be quite significant. Therefore, collaboration between different universities should be encouraged and supported. Some partnerships are already in place but these should be expanded to a nationwide program to help eliminate downtimes, which significantly affect outcomes. Other high-end fabrications such as MBE, MOCVD, IV, III-V quantum devices are advanced and already in place, but they could be expanded to increase capacity.

Key enablers

Optical characterisation on both micro and nano scales is also very important as well as material characterisation on the nano scale.

Figures 24 and 25 (below) show the roadmap and the current and future performance requirements to address this challenge.

Engineering Techniques and Process Optimisation		**What's IN Scope:** Advanced photonic material engineering including GaP metasurfaces, SPE integration, defect exploration in hBN and TMDs, and quantum emitter optimization for high-efficiency applications of single-photon emitters (Including layered materials (LBN,TMD) for photonic applications); **What's OUT of Scope:**	**Desired future (key figures of merit):** g^2(o)=0,Indistinguishability =1 External QE => 1 Electrical drive desired Temperature = As high a possible (Liquid Nz) Scalability - design Vs Real performance, -high yield (>50%) Tunability - 10 nm Gen Rate - 10^9 s^-1
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
2D materials	Design of suitable nano photonics devices for integration of SPE in 2D material via numerical simulation	Controlled fabrication of SPEs(single photon emitter) in 2D materials coupled to photonic structure Understanding of decoherence mechanisms of SPEs in 2D materials Reliable site control for SPEs without compromising optical properties and coherence (all types) Interfacing SPEs with waveguiding devices on	QDs single photon emitter (solid or colloidal) III-V,II VI 2D materials -integration with high performance photonics eg.SiN High temp Quantum emitter/waveguide/SPAD PIC Full integrated active/passive quantum PICs
Molecular material		High purity host material for molecular quantum emitter	
Solid state defects	InGaAs Quantum Dots site controlled growth - high optical quality - integration with charge tuneability	Defect in 2D / diamond / SiC - deterministic ion implantation for site control	
Other	High quality photonics structure to improve the external quantum efficiency Robust quantum light source i.e. topological laser Low loss wave guiding materials/ devices is UV-visible -NIR region	Heterostructure engineering for electrical injection into TMO/hBN quantum emitters Charge stability (blinking, spectral wavering) High gen optical pump SPE all types Different host materials to tailor the crystal field	
Enabling Technologies	• High quality dielectric material development (deposition, characterising) • Process development for passive devices • EBL, RIE, AID sputtering semiconductor or fab dielectric deposition MBE, MOCVD (III-V) • Small scale state-of-the-art laboratories equipped with advanced tools for the synthesis, characterization, and testing of 2-D materials. High purity material growth facilities e.g. MBE, MOVPE, MOCVD for host material synthesis. Controlled defect generation. Dedicated material growth facilities • Routine and advance optical characterisation including micro&nano spectroscopy & imaging • Nano resolution printing and patterning (Nanofabrication facilities) • Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities	• Silicon based integral photons e.g. Cornerstone • Alternative cooling technology operating at LN2 Temp • Heterogeneous/Monolithic integration of dissimilar materials • Advanced fabrication technologies (foundry-like cleanroom, standardization of device fab etc.) • Metrology at nano/atomic scale for quality control. Benchmarking materials/devices, understanding and improvement • (Post processing) AFM vs hard structures providing strain in TMD monolayers for SPE formation • Controlled fabrication for defects in diamond including integration in photonic structures (waveguides, cavities outcoupling, etc) + SIL • III-V growth + nanofabrication • Small scale state-of-the-art laboratories equipped with advanced tools for the synthesis, characterization, and testing of 2D materials. High purity material growth facilities e.g. MBE, MOVPE, MOCVD for host material synthesis. Controlled defect generation. Dedicated material growth facilities. • Nanofabrication facilities • High yield "pick and place" techniques for heterointegration for photonic circuits	• Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities • Active quantum photonic system manipulating >= 10 qubits
Skills and Training	• Photonics design packages (lumerical etc) all years • Visa changes to allow new postdocs to move to the UK • Training and retaining PhD students • Supporting early career researchers. Early career researcher training/workshops in quantum sensing • Developing specialized educational programs at universities to train the next generation of researchers and engineers in quantum technologies and 2D materials e.g. Packaging, materials characterisation, cryogenic characterisation of switches etc. • Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements	• PDk for quantum photonic devices/system fabrication • Visa changes to allow new postdocs to move to the UK • Training and retaining PhD students • Supporting early career researchers. Early career researcher training/workshops in quantum sensing • Developing specialized educational programs at universities to train the next generation of researchers and engineers in quantum technologies and 2D materials e.g. Packaging, materials characterisation, cryogenic characterisation of switches etc. • Integrated national skills program including quantum technology spanning all educational stages and retraining. To incorporate skills such as physics, chemistry, chemical physics, computational modelling, and engineering. Also training specialised technicians • Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements	• Visa changes to allow new postdocs to move to the UK • Training and retaining PhD students • Supporting early career researchers. Early career researcher training/workshops in quantum sensing • Developing specialized educational programs at universities to train the next generation of researchers and engineers in quantum technologies and 2D materials e.g. Packaging, materials characterisation, cryogenic characterisation of switches etc. • Integrated national skills program including quantum technology spanning all educational stages and retraining. To incorporate skills such as physics, chemistry, chemical physics, computational modelling, and engineering. Also training specialised technicians • Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements
Policies	Visa changes to allow new postdocs to move to the UK		
Infrastructure	• Multiple sites for EBL, RIE, Semiconductor fab clean rooms • Modelling of new materials and devices • Nanofabrication facilities • Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities	• Policy for international partnerships to draw in critical capabilities and build supply chain opportunities • International Partnerships and Collaboration especially for fabrication facilities for all of the potential hardware platforms • Pilot production facilities to bridge the gap between laboratory-scale research and industrial-scale manufacturing • Nanofabrication facilities • A UK-based facility for high-quality, thin overgrowth on diamond would enable bottom-up fabrication rather than always relying on top-down of commercial samples • Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities • Advanced lithography systems • PEWD, ALD deposition	• Policy for international partnerships to draw in critical capabilities and build supply chain opportunities • International Partnerships and Collaboration especially for fabrication facilities for all of the potential hardware platforms • A UK-based facility for high-quality, thin overgrowth on diamond would enable bottom-up fabrication rather than always relying on top-down of commercial samples, or international collaborations • Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities • Testing equipment and protocols • Foundry access for fabrication of integrated photonics circuits for III-Vs 2D (1-5years), 2D (10 years), diamond (10years)
Funding	• Funding to employ senior research associates in national facilities able to produce service work and ensure continuity of equipment. A higher level of senior researcher involvement is needed in the growth and processing of materials • Specific grants and funding programs targeting quantum technology and 2D materials research • Every year: GBP 150K 12 month proof of concept grant Around 20 projects/ year	• Every year: GBP 800K 5 year mid term focus or fellowship grants 10 projects/year • Financial support and incentives for local quantum-related industries (policy, tax, tariffs, etc.) • Funding to employ senior research associates in national facilities able to produce service work and ensure continuity of equipment. A higher level of senior researcher involvement is needed in the growth and processing of materials • Specific grants and funding programs targeting quantum technology and 2D materials research	• Every 2 year: GBP 2-3M large size programme grants 10 projects/2 year • Financial support and incentives for local quantum-related industries (policy, tax, tariffs, etc.)
Other	• Establishing collaborative networks in academia with input from industry and research institutions to foster knowledge exchange and interdisciplinary research. • Establish interdisciplinary research teams with chemists, materials scientists quantum physicists and engineers	Establish interdisciplinary research teams with chemists, materials scientists quantum physicists and engineers	

Figure 25: Roadmap for Engineering Techniques and Process Optimisation

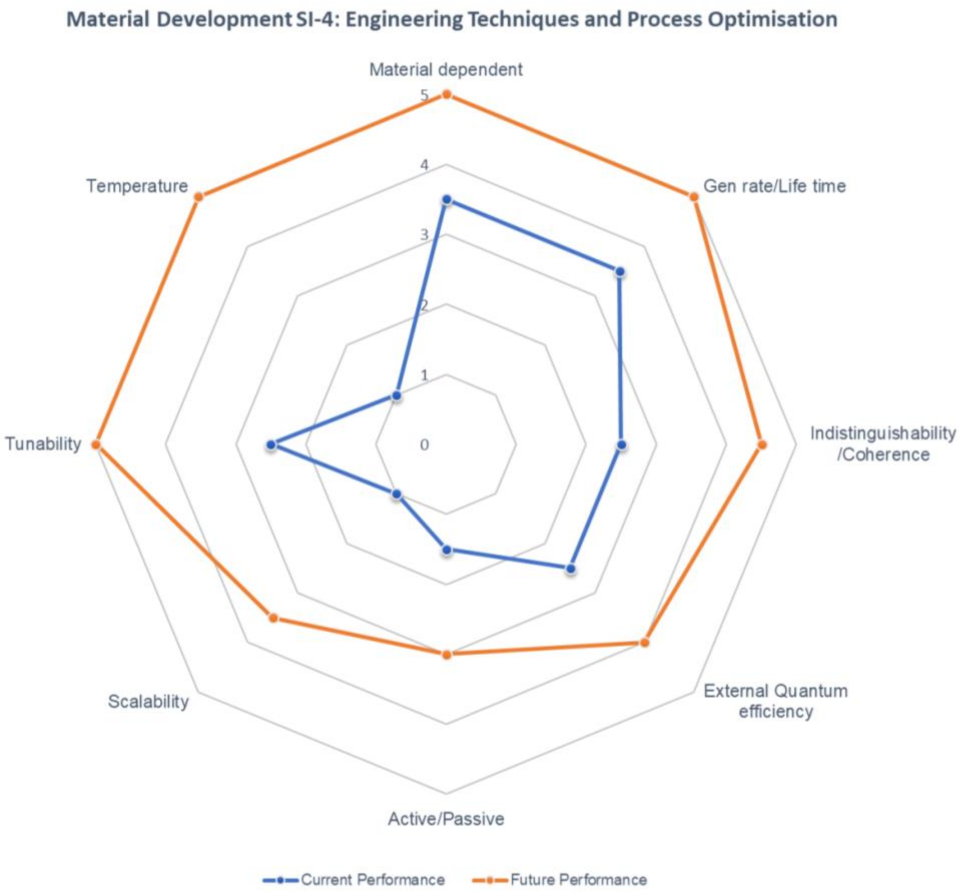

Figure 26: Current and future performance requirements for Engineering Techniques and Process Optimisation (5 = excellent performance, 1 = poor performance)

Further details on improvements that are necessary to achieve desire final performance for this area, are shown in Table 19 (below).

Table 15: Further detail on necessary targets for improvement for achieving desired final performance for Engineering Techniques and Process Optimisation

	InAs QDs	hBn	SiU/NU	Molecule	TMDs
Material dependent	≤ 0.01	~0.01	~0.01		
Indistinguishability /Coherence	~0.98	~0.001-0.7			
Tunability	20nm	Few nm	0.1nm	~1nm	Few nm

Topic 5: Material and Quantum System Discovery and Modelling

Definition and scope

This topic focuses on the design and discovery of new materials or understanding the science behind quantum materials.

Current challenges

The current challenges are around how to facilitate and ideally speed up material discovery and formulation using predictive AI tools and build realistic defect/impurity models of material systems.

There needs to be a joint effort between theorists and experimentalists so material models are representative and applicable across most materials of interests. In particularly, sustainability needs to be incorporated in those models and inform materials design studies. In the longer term, quantum computer based simulations need to be scalable and they should be performed taken into account the specific quantum materials.

Key figures of Merit

The first figure of merit is the ability to predict new engineered quantum materials that can be made in a lab. Currently, there is no sufficient overlap between the prediction of materials and the ability to fabricate them. Fabrication should be done in ways that are controllable, reproducible and potentially in the longer term, scalable.

These supports the second figure of merit – the ability to carry out reliable predictive modelling. This capability already exists for some properties and materials, but the goal should be to be able to achieve this for *all* predictive modelling to meet a reliable standard. The third figure of merit is related to light matter modelling. Specifically, advancing the current understanding of light matter interactions, which will be of key importance for quantum materials. Significant components of materials discovery and design are sustainability and capability, focusing on the purpose and intended use of the materials.

Utilising machine learning and AI to improve material modelling capabilities and to understand how they can contribute to quantum programmes in the future is also an important activity. Initially, the existing tools available need to be utilised, and tested to ensure that they work for specific materials used for quantum applications. In the longer term, simulations on quantum computers could be employed in order to run the large-scale modelling that is needed to truly develop and design new materials with the required performance.

Key enablers

Different strategies can be employed to achieve these goals and enable progression, many of which are related to investment in the workforce through training, retention of employees and payment of researchers who are capable not only of crossing interdisciplinary boundaries between chemistry, physics, and engineering but also of moving between experiment and theory. Such knowledge is required to facilitate the development of materials and the devices for practical applications. The wider research landscape itself would benefit from close interaction between academic research, policy and industry, and beyond that public engagement.

More interdisciplinary collaborations need to be established across disciplines and institutions and in particular between the quantum theory and modelling and experimental communities to enable the development of improvement of materials for quantum applications.

Figures 26 and 27 (below) show the roadmap and the current and future performance requirements to address this challenge.

Material and Quantum Systems Discovery and Modelling		What's IN Scope: Exploring alternative growth techniques like MBE and PEALD; research on materials with higher critical temperatures; High quality thin film materials; Automated discovery and characterisation of spin systems in different materials with optimal measurements; Material discovery and formulation innovation What's OUT of Scope: General FOM device performance stability operational T etc except conversion efficiency, Scale up	Desired future (key figures of merit): Light-matter interaction physics/modelling software Materials design Sustainable materials, Reliable predictive modelling, w agreement, w experiment, More funding for explorative studies in materials discovery, Predict new engineered quantum materials
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
Other	Material discovery and formulation innovation Testing Predictive AI tools e.g., from google for materials quantum discovery	Building realistic defect/impurity models Joint theory + experiment models across all materials interests Sustainability focussed materials design studies	Quantum Computer based simulations, quantum materials Scalability of simulations
Enabling Technologies	Modelling of new materials and devices High-performance computing for first-principles materials calculations		
Skills and Training	• Training retention + paying ECR's • Developing specialized educational programs at universities to train the next generation of researchers and engineers in quantum technologies and 2D materials e.g. Packaging, materials characterisation, cryogenic characterisation of switches etc., • Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements • Training for researchers to acquire skills in effective science communication, and outreach techniques • Training and retaining PhD students • Supporting early career researchers. Early career researcher training/workshops in quantum sensing • Supporting and encouraging more ambitious proposals orthogonal to the mainstream • Government-led development of mission-led roadmaps for quantum impact, spanning fundamental research, development, and innovation • Policy for international partnerships to draw in critical capabilities and build supply chain opportunities • Broad-based and strategic approach to communications with tailored messages to inspire involvement in the quantum sector	• Researchers that straddle both experiment & theory • Dedicated CPD courses for high school teachers. Engagement in schools and beyond • Develop and provide community programmes, online resources, and EDI bursaries • Encourage collaborating with artists specialising in visual arts, music, performance, or other creative disciplines, in order for innovative avenues for communicating complex concepts to be opened • Policy for international partnerships to draw in critical capabilities and build supply chain opportunities • Integrated national skills program including quantum technology spanning all educational stages and retraining. To incorporate skills such as physics, chemistry, chemical physics, computational modelling, and engineering. Also training specialised technicians	
Policies	Closer interaction between expt & modellers & DSIT -> Inform policy Focus on public engagement: bring public in, explain value of quantum		
Infrastructure		More national fabrication facilities	
Funding	Blue sky funding for materials discovery Potential for failure Funding vehicles to attract modelling community		

Figure 27: Roadmap for Material and Quantum Systems Discovery and Modelling

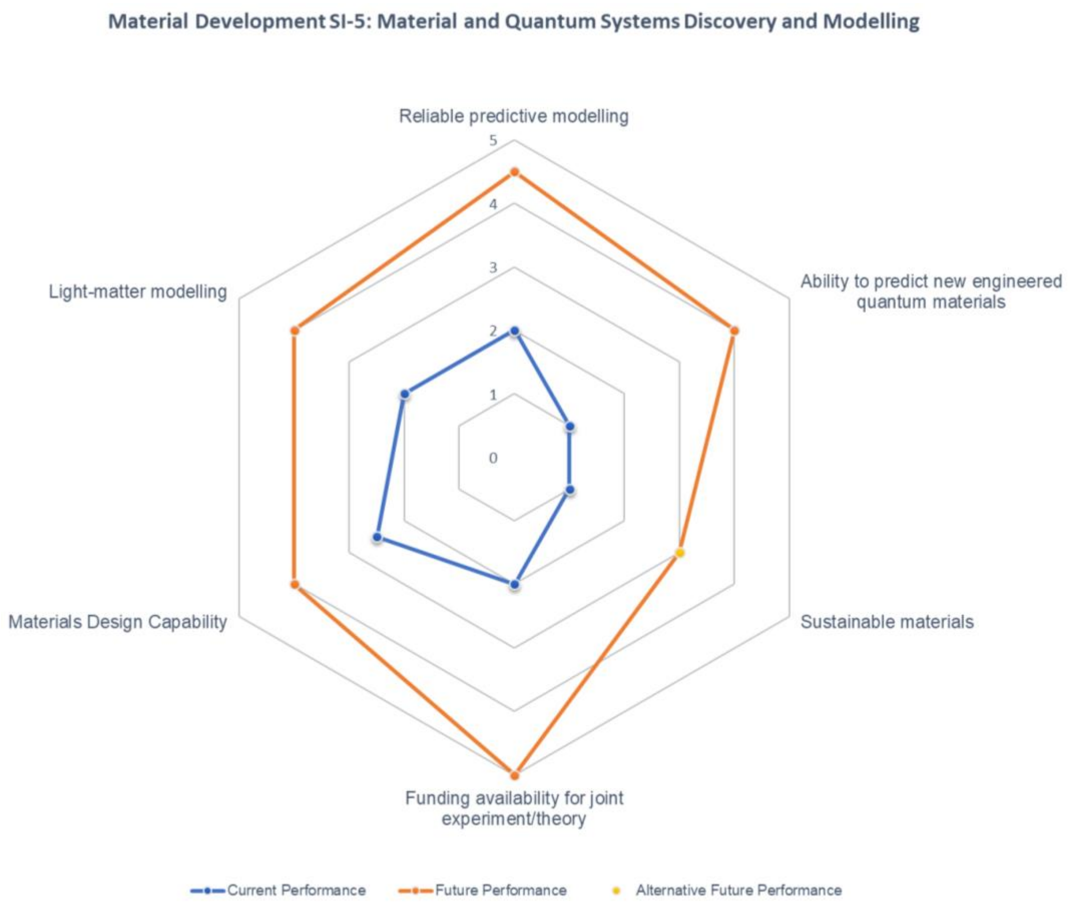

Figure 28: Current and future performance requirements for Material and Quantum Systems Discovery and Modelling (5 = excellent performance, 1 = poor performance)

Topic 6: Device Fabrication

Definition and scope

This topic, includes thin films and device fabrication platforms that included EBL, dry etching, ion beams, national epitaxy. This area is still underdeveloped and many performance parameters need to be significantly improved and demonstrated over the next ten years.

Current challenges

Device fabrications for all of these materials are highly challenging. For example, top-down and bottom-up techniques require slightly different approaches to device fabrication e.g. depositing a superconducting niobium film, requires ultra-high vacuum and super clean environment which is not trivial to carry out. Introducing defects such as boron, to different substrate materials e.g. nitride, diamonds, silicon carbide has different and additional fabrication challenges. Different fabrication techniques e.g. CVD are typically used for 2D materials that require different optimisation protocols. Therefore, a range of different and varied requirements need to be met in terms of device fabrication capabilities.

Key figures of Merit

The key requirements can be summarised in four critical areas.

- First is reproducible and high quality defect/impurity free thin film growth.
- Second is deterministic implantation or creation of advantageous defects.
- Third is the final patterning to create the device.
- Fourth is the final packaging including multilayer interconnects, sealing etc.

Deposition techniques will need both top-down and bottom up processes to deal with the range of inorganic and organic films required. Deterministic implantation of defects by ion or e-beam will need to accommodate a range of materials such as diamond hBN, SiC, ZnO etc. Substrate – film interfaces and strain engineering will play an important part in final property targets. For new semiconductor structures 2.5 and 3D integration will be required. Finally the materials deposited will all require packaging to enable for example RF/microwave to optical interconnects. Overall the goal is interoperability of all components and the desired operating temperature and a suitably long quantum emitter efficiency coupled with a usefully long coherence time.

Key enablers

The enabling technologies are centred around microwave engineering; RF to microwave links and RF to microwave simulations. Another important enabling technology will be flip chip technologies for semiconductors, 2.5D / 3D heterogenous integration. There are additional needs for vibration sensitivities, photonic to microwave integration and quantum interconnects.

Policies should focus on the provision of adequate funding especially for supporting the required infrastructure needs. For instance, having the capability to demonstrate devices at pilot scale, for one hundred devices of any type would be important for showcasing successful devices and materials. The current infrastructure is predominantly lab-based and allows for the creation of perhaps a few devices, which is not reproducible for real-life applications. Having the ability to demonstrate proof-of-principle, is an essential step for engaging with and attracting industry.

Success would be to be able to make a hundred or so devices which are reproducible with high sensitivity, good efficiency, exceptionally high signal-to-noise ratio, stable, and which operate at room temperature. Although quantum computing requires a cold server farm, most other sensor operate at room temperature.

Operating temperature is a current challenge as it is difficult to be maintained the fragile quantum states at room temperature. However, there are many technologies that are used, especially in sensing, which do not require cold temperatures such as gravitometers, magnetometers and more. Reliance specifically on coherence and superposition may not produce positive results, hence the need to expand the approach.

If the UK is serious about developing the quantum technologies industry, government and academia must centralise their resources. Currently, there are many small clean rooms scattered across different locations and this is extremely inefficient and expensive bit for setting up and maintaining. A large fabrication facility (predicted start-up costs in the region of £200 million or £300 million) is therefore an urgent need.

People (postdocs and PhD students) are also needed, but skilled technicians even more so. Such technical staff keep the operations and systems running and provide continuity and stability of operations. As well as centralising/improving access to facilities, it will be advantageous if know-how could be shared more widely. M4QN could support through "technical" meetings where instead of discussing scientific results there is more focus the practicalities. For example, the widespread use of Qudi[29] which is a modular python suite for experiment control and data processing for work on defects would disseminate good practice and save the community reinventing the wheel. This could also involve academic/industrial partners sharing good practice for non-commercially sensitive techniques.

Figures 29 and 30 (below) show the roadmap and the current and future performance requirements to address this challenge.

[29] https://scipost.org/SciPostPhysCore.6.4.065

Device Fabrication		What's IN Scope: Device fabrication platform for EBL, Dry etching etc. like material beam etc. and National Epitaxy Facility; Expand nano-fab, e.g. flip chip lithography for hybrid devices What's OUT of Scope: Device fabrication platform for EBL, Dry etching etc. like material beam etc. and National Epitaxy Facility; Expand nano-fab, e.g. flip chip lithography for hybrid devices	Desired future (key figures of merit): Reproducible, high sensitivity, good efficiency, high SNR, stable room temperature
WHEN	***Short term (1 year)***	***Medium term (5 years)***	***Long term (10 years)***
Materials required			
2D materials	Top-Down Vacuum New writing methods Molecular Solution dep control of self assembly (Bottom-up) challenge=substrate compatibility Nb Need UHV ultra-Clean Deposition	2-D materials CVD Techniques Not UHV - Need glovebox	
Solid state defects	Defects BN, Diamond, SIC challenge Deterministic implantation of defects	Defects by Light/Scanning probe etc	
Enabling Technologies	RF-Optical Links, RF/Microwave engineering,RF/Microwave simulations Thin Film Technologies Flip Chip 2.5,3D semiconductors technology	On chip microwave-photonics integration Vibration isolation - Thermal management for stability Quantum interconnects	
Skills and Training	• Establishing collaborative networks in academia with input from industry and research institutions to foster knowledge exchange and interdisciplinary research • Establish interdisciplinary research teams with chemists, materials scientists quantum physicists and engineers • Technical staff for deposition/cleanroom etc • Funding to employ senior research associates in national facilities able to produce service work and ensure continuity of equipment. A higher level of senior researcher involvement is needed in the growth and processing of materials • Need Quantum engineers+Electrical Engineers especially RF/Microwave engineers • Dedicated CPD courses for high school teachers. Engagement in schools and beyond • Develop and provide community programmes, online resources, and EDI bursaries • Developing specialized educational programs at universities to train the next generation of researchers and engineers in quantum technologies and 2D materials e.g. Packaging, materials characterisation, cryogenic characterisation of switches etc. • Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements • Training for researchers to acquire skills in effective science communication, and outreach techniques • Encourage collaborating with artists specialising in visual arts, music, performance, or other creative disciplines, in order for innovative avenues for communicating complex concepts to be opened • Training and retaining PhD students • Supporting early career researchers. Early career researcher training/workshops in quantum sensing • Integrated national skills program including quantum technology spanning all educational stages and retraining. To incorporate skills such as physics, chemistry, chemical physics, computational modelling, and engineering. Also training specialised technicians		
Policies	Need 20yr vision immune from changes in government		
Infrastructure	Clean room MOCV MBE Sputtering OMBD Glovebox PLD Integration of e.g. organic/inorganic EBL Direct laser writing	• Small scale pilot lines for proof of principle (centralised) • Small scale state-of-the-art laboratories equipped with advanced tools for the synthesis, characterization, and testing of 2D materials. High purity material growth facilities e.g. MBE, MOVPE, MOCVD for host material synthesis. Controlled defect generation. Dedicated material growth facilities • Pilot production facilities to bridge the gap between laboratory-scale research and industrial-scale manufacturing • Infrastructure for large-scale manufacturing of 2D materials and quantum device fabrication (fast waveguide switches, high efficiency single-photon detectors) and wafer scale testing • Nanofabrication facilities • A UK-based facility for high-quality, thin overgrowth on diamond would enable bottom-up fabrication rather than always relying on top-down of commercial samples, or international collaborations • Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities	Super-Fab mainly industry-led
Funding	• Supporting and encouraging more ambitious proposals orthogonal to the mainstream • Financial support and incentives for local quantum-related industries (policy, tax, tariffs, etc.) • Adequate funding from various bodies in research grants to support long-term research projects • Specific grants and funding programs targeting quantum technology and 2D materials research	LOTS	
Other	• Visa changes to allow new postdocs to move to the UK • Policy for international partnerships to draw in critical capabilities and build supply chain opportunities • Government-led development of mission-led roadmaps for quantum impact, spanning fundamental research, development, and innovation		

Figure 29: Roadmap for Device Fabrication

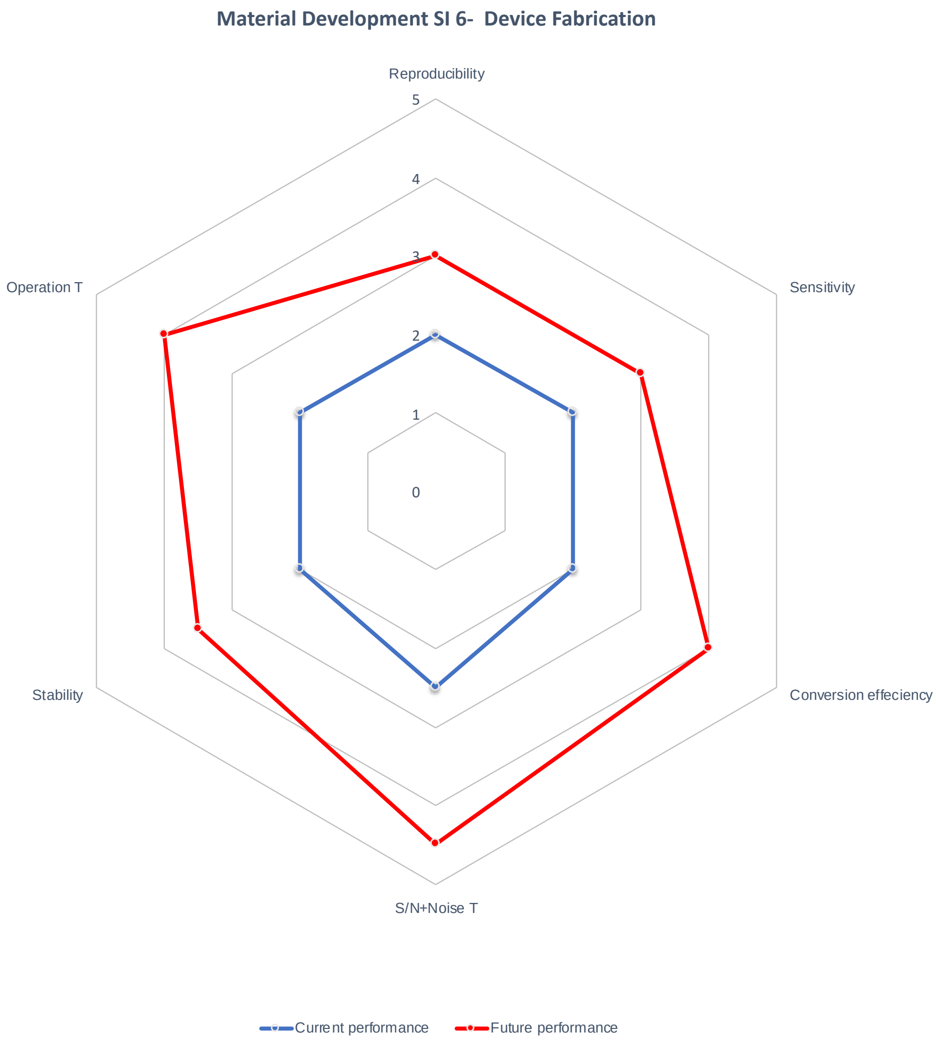

Figure 30: Current and future performance requirements for Device Fabrication (5 = excellent performance, 1 = poor performance)

The intermediate targets for achieving the desired final performance are shown in the table below. In summary, reproducibility refers to the number of devices that can be made with identical performance. Sensitivity is measurement dependent so we have been specific here with respect to magnetic measurements but clearly this is device dependent. Similarly conversion efficiency is extremely dependent on a range of other factors. In the area of quantum transduction we noted that the efficiency of taking a qubit state from the qubit to the optical photon is currently low (10^{-6}) and needs to be unity but there are many other efficiencies that will describe device efficiency. For convenience we reproduce the transduction efficiency from topic 2 "Enabling quantum transduction and frequency conversion for interconnecting qubits and QPUs". Noise temperature is included to describe a key component of future devices particularly for low noise amplifiers and specifically we report results for room temperature masers. Stability can refer to a number of different devices for example we will need to understand the temperature coefficient of frequency for devices that may contain components all exhibiting different coefficients. As an exemplar we use the clock stability for atomic clocks. Finally, the operating temperature for certain devices is mK or certainly 4K and it is possible that this will always be needed for these devices but the aspiration must be room temperature operation.

Table 16: Intermediate targets for achieving the desired final performance for Device Fabrication

	Current	3 years	5 years	10 years
Reproducibility	2-10	10-50	50-10^4	>10^4
Sensitivity	30 pT/√Hz (Reported in [30])	<10 pT/√Hz	<1 pT/√Hz	<100 fT/√Hz (Theoretical sensitivity limit in [31])
Conversion efficiency (quantum transduction)	10^{-6}	10^{-5}	10^{-3}	1
Noise T (K)	5	1	1	<1
Stability (Exemplar PNT clocks)	10^{-8}	10^{-12}	10^{-15}	10^{-18}
Operation T	mK	4K	77K	300K

Key enablers

Several enablers were identified as important for supporting the required developments in this technology area. These were categorised as skills and training, policies, infrastructure, and funding. These are discussed in the following sections.

Skills and Training

Several skills and training programs were needed to develop this technology area. Some of those were important for multiple material development critical in facilitating the growth of the quantum sensing and imaging technology area. These cross-cutting skills and training programs were the following:

- E1) Dedicated CPD courses for high school teachers. Engagement in schools and beyond
- E2) Develop and provide community programmes, online resources, and EDI bursaries
- E3) Developing specialized educational programs at universities to train the next generation of researchers and engineers in quantum technologies and 2D materials e.g. packaging, materials characterisation, cryogenic characterisation of switches etc
- E4) Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements
- E5) Training for researchers to acquire skills in effective science communication, and outreach techniques
- E7) Training and retaining PhD students

[30] Phys. Rev. Applied 19, 044042 (2023) - Fiber-Coupled Diamond Magnetometry with an Unshielded Sensitivity of $30\phantom{\rule{0.1em}{0ex}}\mathrm{pT}/\sqrt{\mathrm{Hz}}$ (aps.org)

[31] [2305.06269] Sensitive AC and DC Magnetometry with Nitrogen-Vacancy Center Ensembles in Diamond (arxiv.org)

- E8) Supporting early career researchers. Early career researcher training/workshops in quantum sensing
- E9) Supporting and encouraging more ambitious proposals orthogonal to the mainstream

The key enablers focus on **attracting new researchers** into the field, **supporting, upskilling and/or continuing to develop existing researchers**, **creating new educational and community programs** to train the next generation of researchers and engineers in quantum technologies and **encouraging innovative thinking** by **supporting proposals that are unconventional** and diverge from the mainstream narrative.

The full list of skills and training enablers proposed is shown in the table below.

Table 17: Skills and Training enablers for the Quantum Sensing and Imaging technology area. The shaded areas indicate the most important enablers required by each of the priority topics.

	1 - Materials Development and Integration	2 - Material Quality and Characterisation Quality Control	3 - Material Synthesis	4 - Engineering Techniques and Process Optimisation	5 - Material and Quantum Systems Discovery and Modelling	6 -Device Fabrication
E1) Dedicated CPD courses for high school teachers. Engagement in schools and beyond						
E2) Develop and provide community programmes, online resources, and EDI bursaries						
E3) Developing specialized educational programs at universities to train the next generation of researchers and engineers in quantum technologies and 2D materials e.g. Packaging, materials characterisation, cryogenic characterisation of switches etc.						
E4) Continuous professional development opportunities for existing researchers and industry professionals to stay updated on the latest advancements						
E5) Training for researchers to acquire skills in effective science communication, and outreach techniques						
E6) Encourage collaborating with artists specialising in visual arts, music, performance, or other creative disciplines, in order for innovative avenues for communicating complex concepts to be opened						

E7) Training and retaining PhD students						
E8) Supporting early career researchers. Early career researcher training/workshops in quantum sensing						
E9) Supporting and encouraging more ambitious proposals orthogonal to the mainstream						
Technical staff for deposition/cleanroom etc						
Need Quantum engineers + Electrical Engineers especially RF/Microwave engineers						
Researchers that straddle both experiment & theory						
PDK for quantum photonic devices/system fabrication and photonic design packages						
Quantum chemistry						
Device design/nanofab						
Materials & quantum characterisation						
Quantum control						
Cryo measurements						
RF Circuitry						
Data skills						
Metrology training uncertainty & instrumentation						

Policy initiatives

Several policy interventions are required to support the further development of Quantum Sensing and Imaging in the UK. The cross-cutting policy initiatives that will positively impact several of the proposed material developments were the following:

- E10) Integrated national skills program including quantum technology spanning all educational stages and retraining. To incorporate skills such as physics, chemistry, chemical physics, computational modelling, and engineering. Also training specialised technicians
- E11) Government-led development of mission-led roadmaps for quantum impact, spanning fundamental research, development, and innovation
- E12) Policy for international partnerships to draw in critical capabilities and build supply chain opportunities
- E14) International Partnerships and Collaboration especially for fabrication facilities for all of the potential hardware platforms
- E15) Visa changes to allow new postdocs to move to the UK

Policy can play an important role to help **co-ordinate the activities at a national level** (both for skills development, and focus areas), establish **international partnerships** and **access to fabrication facilities**, **attract international talent** and **support the budding UK industry**.

The full list of policy initiatives proposed is shown in the table below.

Table 18: Policy initiatives for the Quantum Sensing and Imaging technology area. The shaded areas indicate the most important enablers required by each of the priority topics.

	1 - Materials Development and Integration	2 - Material Quality and Characterisation Quality Control	3 - Material Synthesis	4 - Engineering Techniques and Process Optimisation	5 - Material and Quantum Systems Discovery and Modelling	6 -Device Fabrication
E10) Integrated national skills program including quantum technology spanning all educational stages and retraining. To incorporate skills such as physics, chemistry, chemical physics, computational modelling, and engineering. Also training specialised technicians						
E11) Government-led development of mission-led roadmaps for quantum impact, spanning fundamental research, development, and innovation						
E12) Policy for international partnerships to draw in critical capabilities and build supply chain opportunities						
E13) Broad-based and strategic approach to communications with tailored messages to inspire involvement in the quantum sector						
E14) International Partnerships and Collaboration especially for fabrication facilities for all of the potential hardware platforms						
E15) Visa changes to allow new postdocs to move to the UK						
E16) Financial support and incentives for local quantum-related industries (policy, tax, tariffs, etc.)						
Need 20yr vision immune from changes in government						
Closer interaction between expt & modellers & DSIT -> Inform policy						
Focus on public engagement (bring public in, explain value of quantum), inform end user/ investor and round tables						
Joined up with other policies						

Open-source data policy						
Recruitment and retention						
Support for early adoption & increase demand, low TRL investment						

Infrastructure requirements

Infrastructure is critical in this area to enable researchers and companies develop, test and scale-up promising materials, systems, and architectures. Although some infrastructure maybe specific to the technology or platform chosen, there are some common requirements across the different material developments prioritised as part of this work. The common infrastructure proposed was the following:

- E19) Small scale state-of-the-art laboratories equipped with advanced tools for the synthesis, characterisation, and testing of 2D materials. High purity material growth facilities e.g., MBE, MOVPE, MOCVD for host material synthesis. Controlled defect generation. Dedicated material growth facilities.
- E21) Infrastructure for large-scale manufacturing of 2D materials and quantum device fabrication (fast waveguide switches, high efficiency single-photon detectors) and wafer scale testing.
- E22) Nanofabrication facilities
- E23) A UK-based facility for high-quality, thin overgrowth on diamond would enable bottom-up fabrication rather than always relying on top-down of commercial samples, or international collaborations.

These range from **small-scale laboratories** for **2D material synthesis and characterisation**, **large-scale infrastructures** for **manufacturing quantum devices** and **wafer testing**, **nanofabrication facilities**, and a **UK facility** dedicated to **diamond material innovation**, fostering a seamless transition from high-precision development to practical, large-scale production. Some of these facilities may already exist in the UK, some maybe need to be improved and some will need to be developed to ensure the UK continues to be in the forefront of technological innovation.

The full list of infrastructure proposed is shown in the table below.

Table 19: Infrastructure requirements for the Quantum Sensing and Imaging technology area. The shaded areas indicate the most important enablers required by each of the priority topics.

	1 - Materials Development and Integration	2 - Material Quality and Characterisation Quality Control	3 - Material Synthesis	4 Engineering Techniques and Process Optimisation	5 - Material and Quantum Systems Discovery and Modelling	6 -Device Fabrication
E17) Modelling of new materials and devices				X	X	
E18) High-performance computing for first-principles materials calculations					X	
E19) Small scale state-of-the-art laboratories equipped with advanced tools for the synthesis, characterisation, and testing of 2D materials. High purity material growth facilities e.g. MBE, MOVPE, MOCVD for host material synthesis. Controlled defect generation. Dedicated material growth facilities.	X			X		X
E20) Pilot production facilities to bridge the gap between laboratory-scale research and industrial-scale manufacturing				X		X
E21) Infrastructure for large-scale manufacturing of 2D materials and quantum device fabrication (fast waveguide switches, high efficiency single-photon detectors) and wafer scale testing	X				X	X
E22) Nanofabrication facilities			X	X		X
E23) A UK-based facility for high-quality, thin overgrowth on diamond would enable bottom-up fabrication rather than always relying on top-down of commercial samples, or international collaborations	X			X		X
E24) Materials imaging, spectroscopy and analysis. High throughput photon/spin material assessment capabilities. Optical metrology (HBT interferometry and spin-resonance apparatus). Access to advanced analysis such as in situ XRD, XPS, STEM, TEM. Readily accessible electron paramagnetic resonance facilities				X		X
E25) Testing equipment and protocols		X		X		
Specific fabrication facilities for heterogeneous integration of diverse materials	X					X
Super-Fab mainly industry-led						X
Cleanrooms (e.g. semiconductor)				X		X

MOCV, MBE, Sputtering, OMBD, Glovebox, PLD						
EBL Direct laser writing, RIE and advanced lithography systems						
PEWD, ALD deposition						
Foundry access for fabrication of integrated photonics circuits for III-Vs 2D (1-5years), 2D (10 years), diamond (10years)						
MOCVD / commercially available synthesis component						
Supply chain for critical material ITAR & hostile nations expert capability						

Funding and Collaboration Enablers

Adequate and long-term funding is essential to develop Sensing and Imaging technology area and remain competitive. Interdisciplinary collaborations are also critical as the UK will not have sufficiency in skills and infrastructure. The most mentioned funding areas and collaboration opportunities were the following:

- E26) Funding to employ senior research associates in national facilities able to produce service work and ensure continuity of equipment. A higher level of senior researcher involvement is needed in the growth and processing of materials
- E27) Adequate funding from various bodies in research grants to support long-term research projects
- E28) Specific grants and funding programs targeting quantum technology and 2D materials research
- E29) Establishing collaborative networks in academia with input from industry and research institutions to foster knowledge exchange and interdisciplinary research.
- E30) Establish interdisciplinary research teams with chemists, materials scientists, quantum physicists and engineers
- Interdisciplinary workshop, laboratory exchanges and interlab companies

The funding needed was for **recruitment of experienced personnel**, **research projects**, and **equipment**. **Interdisciplinary collaborations** between different specialities and **laboratory exchanges**, including industry and academia are also important for progressing in this field.

The full list of funding and collaboration enablers proposed is shown in the table below.

Table 20: Funding and Collaboration enablers for Quantum Sensing and Imaging technology area. The shaded areas indicate the most important enablers required by each of the priority topics.

	1 - Materials Development and Integration	2 - Material Quality and Characterisation Quality Control	3 - Material Synthesis	4 Engineering Techniques and Process Optimisation	5 - Material and Quantum Systems Discovery and Modelling	6 -Device Fabrication
E26) Funding to employ senior research associates in national facilities able to produce service work and ensure continuity of equipment. A higher level of senior researcher involvement is needed in the growth and processing of materials						
E27) Adequate funding from various bodies in research grants to support long-term research projects						
E28) Specific grants and funding programs targeting quantum technology and 2D materials research						
Blue sky funding for materials discovery						
Funding vehicles to attract modelling community						
Interdisciplinary workshop, lab exchanges, interlab companies						
Explicit mention of chemistry in quantum funding calls						
Atomically defined materials						
High salaries						
Support for international collaboration and manufacturing industry						
E29) Establishing collaborative networks in academia with input from industry and research institutions to foster knowledge exchange and interdisciplinary research.						
E30) Establish interdisciplinary research teams with chemists, materials scientists quantum physicists and engineers						
Better appreciation of chemistry in National QT programme						
Survey of critical material and critical suppliers						

Positioning, Navigation and Timing

WORKSHOP OUTPUTS

Background

Accurate Positioning, Navigation, and Timing (PNT) data is essential for the functioning of critical civil, commercial, or military infrastructure. Current PNT systems are able to provide real-time operational and logistical information to ensure the correct placement, navigation, and synchronisation of assets. For defence purposes in particular, this is a critical capability.

Presently, satellites and in particularly Global Navigation Satellite System (GNSS) are used as the primary source of PNT information. GNSS signals can be disrupted or manipulated making this technology vulnerable to cyberattacks[32]. Loss of GNSS signal cannot be easily compensated by other technologies such as inertial navigation devices e.g., gyroscopes and accelerometers as they lose their accuracy over time[33]. The loss of GNSS capability even for short periods of time can leave a nation defenceless against a possible attack.

Quantum PNT could be used to increase the accuracy of inertial navigation by orders of magnitude, providing an alternative technology in GNSS-denied environments[34].There is a lot of interest in developing quantum PNT inertial navigation systems for both, military and defence, and civil applications. Some of the opportunities that have been identified by national governments are around miniaturisation and maturation of atomic clocks, quantum accelerometers, magnetometers and gravimeters and integration of quantum and classical sensors to increase sensitivity, accuracy, and precision over extended timeframes[35].

A NATO Review[36] have indicated that some devices may be ready for deployment within the next five years.

Framework of requirements developed for timing

Due to the sensitive and confidential nature of data and information for the development of quantum PNT systems, it was not possible to generate a publicly available roadmap of current challenges and material developments. Instead, the participants elaborated on the main requirements that atomic clocks should have. These progress from atomic clock operating on racks in real-world environments to being miniaturised. Timing domain stability also improving from 10^{-12} to 10^{-18} over a 10-year timeframe.

The main challenges identified that are relevant to all atomic clock sizes and accuracy ranges in real world environments were:

- Developing reliable, high-performance photon sources and detectors
- High sensitivity to environmental factors leading to decoherence in quantum sensing
- Decoherence in quantum systems such as NV, carbon nanotubes, superconducting qubits
- Need for versatile and precise measurement platforms for a wide range of conditions
- Stability and operation of sensing materials
- Demand for more reliable, industry-grade lasers and scalable generation, routing, and distribution of electromagnetic radiation
- Micro and Nanofabrication Challenges

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32 https://www.cisa.gov/topics/risk-management/positioning-navigation-and-timing#:~:text=Positioning%2C%20Navigation%2C%20and%20Timing%20(,PNT%20information%20to%20provide%20services.
33 https://www.usni.org/magazines/proceedings/sponsored/quantum-sensing-new-approach-maintaining-pnt-gps-denied
34 https://rntfnd.org/2023/06/27/quantum-pnt-forging-ahead/
35 https://www.dst.defence.gov.au/strategy/star-shots/quantum-assured-pnt#:~:text=Strategy%20%7C%20Quantum%2DAssured%20PNT&text=%27Position%2C%20navigation%20and%20timing%20data,and%20synchronisation%20of%20Defence%20assets.
36 https://www.nato.int/docu/review/articles/2021/06/03/quantum-technologies-in-defence-security/index.html

- Commercial deployment

The key material developments that need to be considered to address those challenges were:

- Improving materials and device design
- Multidisciplinary R&D, integration of quantum processes in conventional sensors
- Advances in miniaturisation, cryogenic technology and superconducting circuits
- SPAD arrays (for sensitive single-photon detection and 3D imaging)
- Theoretical and technological developments in antenna design
- Assessment of active and passive limits of nanophotonic material candidates at certain wavelengths and their susceptibility to damage by short-wavelengths ration, possible material treatments and passivation
- Advancements in integrated waveguide technology, amplification, low-loss switches
- Research into material choice and ambient temperature effects, control of crosstalk
- Improvements in fabrication of superconducting materials and accuracy of lithography

The requirements framework derived for atomic clocks over the next 10 years is shown in the table below.

Table 21: Requirements framework for atomic clock development

ATOMIC CLOCKS (timing only)	RACK (not controllable environments, real world)	MOUNTABLE	CHIP
	3 years	5 years	10+ years
10^{-12}	• Low noise physics package • Materials for optical frequency generation (new laser materials) for different wavelengths		
10^{-13}		• Low noise photon detection • Miniaturisation & integration • Laser technology: line width, stability • Novel materials: better environmental protection	
10^{-18}			
↓	• Assessment of active and passive limits of nanophotonic material candidates at certain wavelengths and their susceptibility to damage by short-wavelengths ration, possible material treatments and passivation	Chip-based: • optical frequency comb (ofc 3) • HYBRID nonlinear oxides on silicon photonics	• Miniaturisation & integration • Ability to test, prototype and scale up • Ability to prototype with dirty fabs (fabs capable of handling multiple materials) • Test/prototype, scale-up, packaging & integration, facility

Conclusions

The study for M4QN focused on addressing critical challenges in three key technology areas of quantum computing and communications, sensing and imaging, and PNT. A two-day roadmapping workshop was conducted with participants from relevant parts of academia and industry to identify material developments required to position the UK as a leader in the quantum-enabled economy and to guide future EPSRC funding and materials investment.

Material challenges

Overall, 44 challenges were identified through desk research and participants' input pre-workshop for Computing and Communication area, and 36 challenges for Sensing and Imaging area. During the workshop the participants reviewed, edited, and prioritised the list of challenges.

Three main **common challenges** were identified across all three technology areas were the following and included:

1. Developing versatile, precise characterisation tools for quantum platforms and metrology, capable of accurate measurements across varying conditions, including in vivo calibration, internal strain, nanoscale spectroscopic characterisation at low-temperatures, in-situ materials characterisation interfaces and operation under vacuum.
2. Micro and nanofabrication challenges involving achieving precise control and positioning of colour centres in diamond for solid-state technologies, alongside ensuring purity control, defect characterisation, surface quality management, and functionalisation to enhance quantum sensing capabilities.
3. Efficient photonic integration challenges including coupling solid-state quantum emitters with photonic networks, focusing on on-chip quantum dot based photonic sources for desired states, high brightness site control.

In addition to challenges that spanned across the areas, **four challenges** were identified in the **Computing and Communications** area:

- Low temperature electronics integration
- Enabling quantum transduction and frequency conversion for interconnecting qubits and QPUs
- Characterisation of performance and routes to noise resilience including against correlated errors
- Investigation and discovery new qubit systems including 2D, topological and spintronics systems

Four additional challenges were identified in the **Sensing and Imaging** area:

- Electrical readout and manipulation of quantum states; controllable coupling of individual solid-state; Integration of quantum emitters with photonic networks for efficient coupling; building devices with tailored capabilities for specific sensing applications e.g., nano-NMR; high-yield assembly of molecular devices; design molecules for devices rather than devices around molecules (architecture)
- Sustainability - materials, processes, devices, operation; Consideration of energy and resource investment in tech development
- Integration of quantum materials into robust packaging for real-world systems; micro -& nano fab for all materials –precise
- Integration challenges (scalability/robustness). Inhomogeneity of poorly controlled/characterised materials/interfaces/devices

Five additional challenges were identified in the **Timing** technology area:

- Developing reliable, high-performance photon sources and detectors

- High sensitivity to environmental factors leading to decoherence in quantum sensing
- Decoherence in quantum systems such as NV, carbon nanotubes, superconducting qubits
- Stability and operation of sensing materials
- Demand for more reliable, industry-grade lasers and scalable generation, routing, and distribution of electromagnetic radiation

Material developments

For **Computing and Communications** area specific **material developments** were explored further in small groups, which were formed based on the priority challenge they were addressing:

1. Low-temperature electronics integration
2. Enabling quantum transduction and frequency conversion for interconnecting qubits and QPUs
3. Characterisation of performance and routes to noise reduction. Resilience
4. Develop and Maintain characterisation tools for quantum platforms and metrology
5. Defect Engineering
6. Efficient photonic integration of solid state quantum emitters
7. Investigate and discover new qubit systems including 2D, topological and spintronics systems

Overall, 37 potential material developments were identified via participant input and literature review in the **Sensing and Imaging** area. The list was reviewed and refined further during the workshop. The refined list was assessed using two different and broadly separate considerations: impact and feasibility selected prior to the workshop by the M4QN steering Committee. The material developments were prioritised and consolidated to identify six **material development** areas that were then further explored in the workshop in small groups:

1. Materials Development and Integration - Multifaceted material integration including heterojunctions, nanophotonic device fabrication, and precise interfacing techniques; Development of materials towards on-chip photonic systems, e.g., integration of source/transmitter and receiver/detector; Ultra low-loss optical materials for quantum photonic integrated circuits; Developing new materials for non-linear optics in quantum photonics.
2. Material Quality and Characterisation Quality Control - Material Quality and characterisation quality control: Quality control in defect materials e.g., SiC, Diamond, etc.; Tailoring doping, isotopic composition, purity, with resilient UK supply; Material quality and characterisation including trap density management, defect control, nano-atomic characterisation, and polycrystalline structure understanding.
3. Material Synthesis - Establishing control over inter-molecular structured interactions (e.g., by synth-DNA conjugation); Atomically precise material synthesis at scale.
4. Engineering Techniques and Process Optimisation - Advanced photonic material engineering including GaP metasurfaces, SPE integration, defect exploration in hBN and TMDs, and quantum emitter optimization for high-efficiency applications of single-photon emitters (Including layered materials (LBN, TMD) for photonic applications).
5. Material and Quantum Systems Discovery and Modelling - Exploring alternative growth techniques like MBE and PEALD; research on materials with higher critical temperatures; High quality thin film materials; Automated discovery and characterisation of spin systems in different materials with optimal measurements; Material discovery and formulation innovation.
6. Device Fabrication - Device fabrication platform for EBL, Dry etching etc. like material beam etc. and National Epitaxy Facility; Expand nano-fab, e.g., flip chip lithography for hybrid devices.

The key **material developments** that need to be considered to address challenges related to **Timing** application were:

- Improving materials and device design
- Multidisciplinary R&D, integration of quantum processes in conventional sensors

- Advances in miniaturisation, cryogenic technology and superconducting circuits
- SPAD arrays (for sensitive single-photon detection and 3D imaging)
- Theoretical and technological developments in antenna design
- Assessment of active and passive limits of nanophotonic material candidates at certain wavelengths and their susceptibility to damage by short-wavelengths ration, possible material treatments and passivation
- Advancements in integrated waveguide technology, amplification, low-loss switches
- Research into material choice and ambient temperature effects, control of crosstalk
- Improvements in fabrication of superconducting materials and accuracy of lithography

Figures of Merit

The **two common Figures of Merit (FoM)** that spanned across Computing and Communications, and Sensing and Imaging areas were the following:

- Operating temperature (inter-operability of all components)
- Quantum emitter efficiency and coherence, emission collection, indistinguishability, transfer time, and decoherence dynamics, coherence time/number of gates

Additional FoMs identified for **Computing and Communications** were:

- Multiplexing and inter-qubit coupling: Managing 1M qubits with 1000 wires at 4K and quantifying qubits per chip
- Gate fidelity, fidelity of transformed qubits
- Cryo-compatibility - Evaluating transducer capacity before overheating qubits, thermal noise impact, temperature stability, and quality factor in relation to qubit heating and coherence times
- Crosstalk minimisation - Inverse error rate in number of transfers including added thermal noise
- Isotopic purity, tunability and inhomogeneity

Additional FoMs identified for **Sensing and Imaging** were:

- Routing and manipulations of photons, optical loss, maintaining coherence, non-linear conversion efficiency; Conversion efficiency
- Uniformity/Reproducibility/ Manufacturability/Yield; Suitable characteristics techniques hardware & data methods, Robustness and reproductivity, Applicability wide range of materials and applications; In SITU/operando Reproducibility
- Scalability (for individual devices)

Enablers

There are skills and training requirements across all technology areas. These are both attracting new researchers into the field, supporting, upskilling and/or continue to develop existing researchers and creating new educational and community programs to train the next generation of researchers and engineers in quantum technologies. Encouraging innovative thinking by supporting proposals that are unconventional and diverge from the mainstream narrative is also important. Policy can play an important role to help co-ordinate the activities at a national level (both for skills development, and focus areas), establish international partnerships and access to fabrication facilities, attract international talent and support the budding UK industry.

Infrastructure is critical in helping the UK quantum community advance in this area. This range from modelling and high-performance computing to small-scale laboratories for 2D material synthesis and characterisation, nanofabrication facilities, large-scale infrastructures for manufacturing quantum devices and wafer testing pilot production facilities and open foundries to enable industrial-scale manufacturing in the UK. A UK facility dedicated to diamond material innovation, fostering a seamless transition from high-precision development to practical, large-scale production is also needed for sensor and imaging applications. The infrastructure should also include a range of necessary imaging, spectroscopy, and analysis techniques necessary for the discovery, characterisation and performance evaluation of different concepts and systems.

Some of these facilities may already exist in the UK, some maybe need to be improved and some will need to be developed to ensure the UK continues to be in the forefront of technological innovation.

The funding needed was for recruitment of experienced personnel, research projects, and equipment. Interdisciplinary collaborations between different specialities, and laboratory exchanges including industry and academia are also important for progressing in this field.

Appendix 1: Participants list

Participant name	Institution
Neil Alford	Imperial College London
Iddo Amit	Durham University
Arzhang Ardavan	University of Oxford
Daan Arroo	Imperial College London
Mete Atature	University of Cambridge
Nicky Athanassopoulou	IfM Engage, Facilitator
Max Attwood	Imperial College London
Michael Baker	University of Manchester
Nilanthy Balakrishnan	Keele University
Pete Barry	Cardiff University
Sam Bayliss	University of Glasgow
Thea Bjøranger	IfM Engage, Facilitator
Jessica Boland	University of Manchester
Cristian Bonato	Heriot-Watt University
Alice Bowen	University of Manchester
Jonathan Breeze	University of Sheffield
Evgeny Chekhovich	University of Sheffield
Alex Clark	University of Bristol
Steven Clowes	University of Surrey
Charlie Cobb	IfM Engage, Facilitator
Maddison Coke	University of Manchester
Malcolm Connolly	Imperial College London
Shelly Conroy	Imperial College London
Joseph Cotter	Imperial College London
Monica Craciun	University of Exeter
Iain Crowe	University of Manchester
Richard Curry	University of Manchester
Zoe Davidson	BT
Anke Davis	EPSRC
Johann de Silva	DSIT
Kaveh Delfanazari	University of Glasgow
John Devaney	NPL
Philip Dolan	Nu Quantum
Scott Dufferwiel	Aegiq
Emrys Evans	Swansea University
Helen Ewles	Royal Academy of Engineering
Vladimir Falko	University of Manchester
Dorian Gangloff	University of Cambridge
Megan Grace-Hughes	London Centre for Nanotechnology
Ben Green	University of Warwick
Peter Haynes	Imperial College London

Jon Heffernan	University of Sheffield
Sandrine Heutz	Imperial College London
Bo Hou	Cardiff University
Yaonan Hou	Swansea University
Nathaniel Huáng	NPL
Imoh Ilevbare	IfM Engage, Facilitator
Olga Kazakova	NPL
Diana Khripko	IfM Engage, Facilitator
Peter Knight	NQTP
Helena Knowles	University of Cambridge
Qiang Li	Cardiff University
Edmund Linfield	University of Leeds
Huiyun Liu	University of Manchester
Isaac Luxmoore	University of Exeter
Margherita Mazzera	Heriot-Watt University
Elizabeth McKenzie	University of Manchester
Phil Meeson	Royal Holloway, University of London
Jan Mol	Queen Mary University of London
Thomas Moore	University of Leeds
Juliana Morbec	Keele University
Gavin Morley	University of Warwick
Alessandro Mottura	University of Birmingham
Ruth Oulton	University of Bristol
Charlotte Ovenden	Aegiq
Dadhichi Paretkar	IfM Engage, Facilitator
Denise Powell	Compound Semiconductor Centre
Tim Prior	NPL
Alex Ramadan	University of Sheffield
Elisa M Sala	University of Sheffield
Satoshi Sasaki	University of Leeds
Rosemary Scowen	Toshiba Europe Limited
Jason Smith	University of Oxford
Mingchu Tang	University College London
Alexander Tartakovskii	University of Sheffield
James Thomas	Queen Mary University of London
Isabella von Holstein	Imperial College London
Jess Wade	Imperial College London
Sebastian Wood	NPL
Huanqing Ye	University of Manchester
Xin Yi	Heriot-Watt University
Anatoly Zayats	King's College London
Jake Zipfel	NPL
Hamid Ohadi	
Hannah Stern	

Robert Hardeman	
Stuart Nicholas Holmes	
Jithin Kannanthara	
Meg Smith	
Hannah Price	

Appendix 2: Methodology

The delivery of the roadmapping workshop consisted of three parts: Planning and Design, the Workshop, and the Report.

Planning and Design

During the planning and design phase the following activities took place:

(a) Confirm and detail the aims and scope of the workshop.
(b) Discuss and design the workshop methodology and process.
(c) Design the workshop templates necessary for any pre-work activities and the workshop.
(d) Agree on the selection criteria important for selecting the material developments.
(e) Agree the detailed workshop agenda.

Finalise any logistical arrangements required (venue, catering etc).

Workshop

A two-day workshop was designed to explore the themes of **challenges** and **material developments** in the context of three technology areas: Quantum Computing and Communications; Quantum Sensing and Imaging; and Quantum Positioning, Navigation and Timing (PNT). The workshops aimed to develop one overarching roadmap to create case studies for investment by the government.

81 external participants from across academia, industry and government attended the workshop with the full list attached in Appendix 1.

The workshop agenda is shown in the table below.

Table 22: Workshop agenda

	Day 1 – Monday 08 January 2024
13:00	Welcome & Workshop Introduction
13:30	Keynote Lecture Prof. Sir Peter Knight
14:00	STEP 1: Identifying Key Challenges & Material Developments
15:15	Break
15:30	STEP 2: Review & Prioritisation of Key Challenges
16:15	STEP 3: Review & Prioritisation of Materials Challenges
17:15	Recap
17:30	Close
19:00	Dinner | Hornton Grange Building, Lloyd Suite
	Day 2 – Tuesday 09 January 2024
09:00	Recap of previous day’s outputs
09.30	STEP 4: Materials Development Deep Dive Pt. 1
10:30	Break
10:45	STEP 5: Materials Development Deep Dive Pt. 2
12:30	Workshop Outputs, Review & Feedback
13:00	Lunch
14:00	Review of all topics
14:45	Next Steps and Closing Remarks
15:00	Close

Reporting

IfM Engage transcribed all output from the workshop in an electronic format, drafted the current report and distributed it initially to the M4QN participants for reviewing the accuracy of transcriptions and subsequently to that to the M4QN committee for review and wider circulation.

Each technology area is reported separately but overarching challenges, material developments, Figures of Merit and enablers across technology areas are also summarised and presented in the executive summary.

Appendix 3: Full list of challenges for Computing and Comms

	Computing and Comms Consolidated input - Material Challenges	Roadmap layer	Timescale	Votes	Grouped Challenge number and title
CC-MCh3	Scalability (1M+ qubits) for fault-tolerant computing	Technology	10 years	11	8. Scalability (1M+ qubits) for fault-tolerant computing
CC-MCh5	Scaling challenges in Superconducting qubit systems due to qubit-to-qubit variations (temporal and spatial)	Other	5 years	7	
CC-MCh20	Challenges in discovering new and high-quality material solutions, in fabrication methods and enhancing non-linear material properties, topologies, future materials etc	Quantum	10 years		
CC-MCh5a	Scaling challenges due to decoherence	Technology	Now		
CC-MCh6	Challenges in scalability of colour centre systems	Other	5 years		
CC-MCh8	Noise induced by two-level fluctuators and quasiparticle tunnelling or resistive loss at the interface in superconducting qubit systems	Quantum	Now	15	3. Characterisation of performance and routes to noise. Resilience
CC-MCh9	Noise induced by nuclear spins and charge traps at the interface in QD systems. Correlated errors	Quantum	Now		
CC-MCh10	Noise induced by dangling bonds, rough surface, host material lattice defects in colour centre systems	Quantum	10 years		
CC-MCh11	Electric-field noise in surface trapped ions systems	Technology	Now		
CC-MCh23	Interface quality, stability and reproducibility of junction barriers	Integration	Now		
	Exploring courses of decoherence in D100 qubit super devices	Quantum	Now		
	Search for quieter Josephson junction systems beyond A12 03/Al	Quantum	Now		
CC-MCh45	Maintaining coherence in ion implanted Rare-earth ions in crystals				
CC-MCh14	Quantum computation with engineered and artificial spin structures	Quantum	10 years		
CC-MCh15	Challenges in material control and purity levels	Quantum	Now		
CC-MCh17	Challenges for III-V optical active semiconductor QDs	Technology	5 years		
CC-MCh18	Addressing limitations, challenges (temperature, material, collisions, reliable generation), crosstalk and wavelengths in trapped ion systems	Quantum	5 years		
CC-MCh21	Challenges in qubit fabrication, characterisation, and device integration in semiconductors and 2D materials e.g. contact noise, SPE performance, entanglement etc	Integration	Now	1	

CC-MCh2	Integration challenges of quantum emitters with photonic networks; nonlinear optical devices for efficient coupling	Integration	Now	10	6. Efficient photonic integration of solid state quantum emitters
CC-MCh16	Challenges in building a fibre-linked quantum network with diamond NV, SiC– and group IV split vacancy centres in colour centres in wide-bandgap materials	Integration	5 years		
CC-MCh21a	Fabrication of qubits in 2D semiconductor materials	Integration	Now		
CC-MCh21b	Characterisation pf qubits in 2D/semiconductor materials	Integration	Now		
CC-MCh21c	Integration of qubits in 2D/semiconductor materials	Integration	Now		
CC-MCh22	Identifying and growing improved bulk crystals with reduced nuclear spin concentration and ultra-low rare-earth background impurities in Rare-earth ions systems	Quantum	5 years	9	
CC-MCh24	Address qubit coherence times, reducing losses and decoherence in different devices, systems and spin types	Quantum	Now		
CC-MCh25	High-fidelity rearrangement of atoms and scaling the size of ultracold atom arrays systems	Technology	10 years		
CC-MCh1	Integration challenges with low-temperature electronics	Integration	5 years	19	1. Low temperature electronics integration (4K & lower)
CC-MCh27	Electrical interconnection and packaging challenges including photonic packaging. Thermal	Integration	Now		
CC-MCh27b	Thermal management of electrical interconnects	Integration	5 years		
CC-MCh26	Challenges e.g. homogeneity with Superconducting materials for single photon detectors	Devices	Now	7	
CC-MCh28	Challenges with performance in miniaturizing optical sources, detectors, and components.	Device	Now		
	Exploring preservation techniques for surplus of superconducting technology	Device	Now		
CC-MCh30	Generation of correlated photons for quantum technologies	Quantum	5 years		
CC-MCh31	Micro and Nanofabrication challenges of control and positioning for technologies on solid state	Technology	5 years	13	5. Micro and Nanofabrication challenges of control and positioning for technologies on solid state
CC-MCh29	Control, variability and purity in single-photon emitters (SPEs)	Other (materials)	Now	10	
CC-MCh32	Initialization, Control, and Readout of Individual Spins	Other	Now		
CC-MCh41	Process contamination during etching making high-yield, scalable fabrication challenging	Other	Now		
CC-MCh34	Challenges on growth, spatial distribution and inhomogeneous line broadening, making successively emitted photons partly distinguishable of superconducting thin films	Other	5 years		

CC-MCh4	Scaling qubits in donor-based silicon technologies	Technology	5 years	15	2. Enable quantum transduction and frequency conversion for interconnecting qubits and QPUs
CC-MCh5b	Scaling challenges due to qubit fab quality	Technology	5 years		
CC-MCh35	Enable sharing entanglement across chips to implement non-local error correcting codes transduction	Integration	5 years		
	Raising superconducting qubit operation frequencies	Technology	5 years		
	Improve nanofab quality beyond current state-of-the-art for Josephson junctions	Technology	5 years		
CC-MCh36	Infrared luminescence enhancement in GaN for quantum cryptography for telecoms	Other	Now		
CC-MCh37	High harmonic generation (HHG) for light-matter interaction studies	Quantum	Now		
CC-MD15	Application of ESR-STM in quantum platforms	Other	Now	14	7. Develop and maintain characterisation tools for quantum platforms and metrology
CC-MCh33	Deterministic fabrication of on demand single photon sources.	Quantum	Now		
CC-MCh38	Characterisation Tool for Quantum Platforms. Develop standards (methodology) assisting tools	Quantum	Now		
CC-MCh38b	Development of automation and new techniques for QM	Quantum	Now		
	Exploring MoN, TiN, Ta etc as novel architectures	Quantum materials	Now		
CC-MCh39	Engineering of solid-state quantum systems for high performance	Device	10 years		
CC-MCh40	Manipulating multiple chains of ions in ion traps	Technology	10 years		
CC-MCh42	Room-temperature functionality of SPEs	Environmental	10 years	2	
CC-MCh7	Achieving high-precision QAHE under Zero B Field and high temperature	Quantum	5 years	9	4. Investigate and discover new qubit systems including 2D, topological and spintronics systems
CC-MCh12	Large noise magnitude in materials like Bi-based TIs and graphene	Quantum	5 years		
CC-MCh13	Noise induced by proximity hard gap and defect density in nanowire interface in Majorana zero modes	Quantum	10 years		
CC-MCh19	Realization and investigation of QHE in pristine TI materials	Quantum	5 years		
CC-MCh43	Proving the existence of the qubit (MZM in case of hybrid S/S.C. nanowires) in TQC material solutions	Quantum	5 years		
CC-MCh44	Development of qubits in 2D quantum materials like TMDCs	Quantum	5 years		
CC-MD30	Implementing quantum error correction protocols, including topological surface codes, in 2D qubit arrays controlled by a 3D network of electrodes	Other	5 years		
	Multi-scale modelling simulation			4	

Appendix 4: Full list of topics for Computing and Comms

	Computing and Comms Consolidated input – Material developments	Roadmap Layer	Timescale
CC-MD1	Systems combining MTI material thin films and trivial insulator layers, or combining QAHE systems with other materials or techniques, to create new configurations	Materials integration	Now
CC-MD2	Research on contact materials e.g. epitaxial crystalline Ai shells on InAs nanowires and InSb nanowires to reduce noise and maintain structural integrity	Materials integration	5 years
CC-MD3	CMOS-compatible materials and 3D integration techniques e.g. Silicon-based quantum dots, Tantalum based planar transmons and gatemons, Er^{3+}-doped $CaWO_4$, Si, or TiO_2 etc	Materials integration	Now
CC-MD4	Integration of quantum emitters with photonic structures. Ultrafast Rydberg- or photon-kick-based gates, integrated electronics, quantum LEDs, etc.	Materials integration	Now
CC-MD5	Assessment of active and passive limits of nanophotonic material candidates at certain wavelengths and their susceptibility to damage by short-wavelengths ration	Material discovery	10 years
CC-MD6	Development of nano-fabrication techniques to integrate SPEs with atomically thin lenses and metasurfaces, photonic and plasmonic cavities	Materials integration	5 years
CC-MD7	Optimizing growth techniques, material quality, and introducing diode structures for electronic noise minimization, surface passivation to reduce surface charge fluctuations. Exploration of different synthetic methods	Modify existing materials	Now
CC-MD8	Data-driven material discovery of and advances in 2D material growth and systems	Material discovery	5 years
CC-MD9	Modification of existing materials through more precise defect engineering	Modify existing materials	5 years
CC-MD10	Integration of materials for quantum information processing and communication e.g. spins/photons	Materials integration	10 years
CC-MD11	Symmetric device design including film thickness engineering in Superconducting qubit systems	Modify existing materials	5 years
CC-MD12	Use of superconductors (Nb, YBCO) in Surface trapped ions systems. Lithographic scalability in superconducting qubits; advanced fabrication techniques for ion traps	Materials integration	5 years
CC-MD13	Device fabrication optimisation, techniques and capabilities. Optimizing fabrication processes, exploiting charge depletion methods, and high-temperature annealing to reduce inhomogeneous broadenings	Other	5 years
CC-MD14	Host materials e.g. SiC, nanodiamond etc. for qubits in colour centre systems. Improved surface treatments in Colour centre systems	Materials integration	5 years
CC-MD15	Application of ESR-STM in quantum platforms	Other	Now
CC-MD16	Low-strain diamond substrate synthesis and exploration of different surface terminations (oxygen, nitrogen, fluorine, and more) and growth techniques	Modify existing materials	Now
CC-MD17	Systematic study of doping e.g. Substitutional Doping by the Same-Group Elements, Extrinsic Elemental Doping, Oxygen doping in Superconducting qubit systems etc.	Modify existing materials	5 years
CC-MD18	Control and detection of multiple spins on surfaces for quantum computation	Other	10 years
CC-MD19	Building high-power lasers at conventional tweezer wavelengths, reducing trap depth required to load atoms	Other	5 years
CC-MD20	Scalable distribution of electrical and optical waveguides, cryo-compatible in-vacuum control electronics	Other	5 years
CC-MD21	Research on and application of high temperatures in fabrication	Modify existing materials	10 years
CC-MD22	Development of small optical components	Other	10 years
CC-MD23	Fabrication/development of ion traps on glass substrates for improved performance	Other	5 years
CC-MD24	Using SiC in different applications to enhance coherence time	Other	Now
CC-MD25	Use of GaP for efficiency and improved production outcomes including optical devices and metasurfaces	Other	5 years

CC-MD26	Investigating and utilizing defect and strain engineering in 2D materials like TMDs and hBN	Modify existing materials	5 years
CC-MD27	Improving sensitivity of techniques like SIMS and ESR, and using nitrogen-vacancy centres for complementary spectroscopy. Low-temperature microscopy. Atom-by-atom manipulation	Other	Now
CC-MD28	Different processes for reducing damage/defects to the surface and making it smooth	Modify existing materials	5 years
CC-MD29	Exploration of alternative substrate materials to sapphire and silicon	Modify existing materials	Now
CC-MD30	Implementing quantum error correction protocols, including topological surface codes, in 2D qubit arrays controlled by a 3D network of electrodes	Other	5 years
CC-MD31	Access to new materials e.g. adhesives and techniques for application	Material discovery	Now
CC-MD32	Optimization of dielectric encapsulation processes and material interface engineering	Materials integration	Now
CC-MD33	Electron mobility characterisation of wafer-scale Si	Other	Now
CC-MD34	Spontaneous Magnetization with Higher Curie Temperature	Other	10 years
CC-MD35	Enhancing the QAHE observation temperature and efficiency of edge mode manipulation	Other	10 years
CC-MD36	Exploring long-range qubit coupling schemes like electrical dipolar interactions, coupling spin qubits to microwave resonators	Other	10 years
CC-MD37	Strain engineering to decouple ground orbital states from phonons, improving coherence time in group IV split vacancy centres	Modify existing materials	10 years
CC-MD38	Synthetic strategies and assembly schemes for wafer-scale homogeneity; low-energy ion implantation and bottom-up synthesis methods	Modify existing materials	10 years
CC-MD39	New materials that emit telecom C- or O-band	Material discovery	10 years
CC-MD40	Addressing materials loss issues at superconducting junctions	Other	Now
CC-MD41	Multi-module integration of TSVs, photonics, and planar ion traps	Materials integration	5 years
CC-MD42	Utilization of TMDCs for their spin-orbit coupling and valley-protected spins for robust qubits	Modify existing materials	5 years
CC-MD43	Electron beam irradiation to enhance infrared luminescence in GaN, relevant for fibber-based quantum cryptography systems	Other	5 years
CC-MD44	Development of compact spontaneous parametric down-conversion (SPDC) sources based on nonlinear metasurfaces	Material discovery	10 years
CC-MD45	Exploration of biexciton complexes and fine-structure splitting tuning for entangled photon generation	Material discovery	10 years

Appendix 5: Full list of challenges for Sensing and Imaging

	Sensing and Imaging Consolidated input - Material Challenges (1/3)	Roadmap layer	Timescale
SI-MCh1	Technological difficulties in controlling microwaves compared to optical photons. Limited efficiency of photodetectors for quantum microwaves	Technology	Now
SI-MCh2	Integration challenges (scalability/robustness). Inhomogeneity of poorly controlled/characterised materials/interfaces/devices	Integration	Now
SI-MCh3	Integration of quantum materials into robust packaging for real-world systems	Integration	10 years
SI-MCh4	Integration of quantum emitters with photonic networks for efficient coupling	Integration	5 years
SI-MCh5	Scaling up manufacturing challenges	Other	5 years
SI-MCh6	Material quality challenges e.g. inhomogeneity of poorly controlled/characterised materials/interfaces/devices	Other	5 years
SI-MCh7	Modelling challenges	Device	Now
SI-MCh8	Improving accuracy and resolution and ideally sensing magnetic interactions at atomic scale	Technology	Now
SI-MCh9	Developing characterisation tools for quantum platforms e.g. calibration in vivo, internal strain, and environmental variables affecting sensor effectiveness	Other	Now
SI-MCh10	Advanced quantum imaging techniques for enhanced perception (detecting objects out of line of sight, quantum ghost imaging, sub-noise imaging)	Technology	10 years
SI-MCh11	Efficient generation of quantum states of light in quantum illumination, correlated photon production, HHG applications, and enhancing sensitivity in quantum radar technologies	Quantum	10 years
SI-MCh12	Electric-field noise in surface and crosstalk challenges in trapped ion systems including scalability of control systems, gate infidelity, managing heating in microstructured circuits, and manipulating multiple ion chains	Quantum	5 years
SI-MCh13	Optical routing in waveguides, active modulation and switching at blue and ultraviolet wavelengths in Trapped ions systems	Integration	10 years
SI-MCh14	Increasing information density in trap architectures, addressing anomalous heating, and collisions with background gas particles in Trapped ion systems	Quantum	10 years
SI-MCh15	Identifying and growing improved bulk crystals with reduced nuclear spin concentration and ultra-low rare-earth background impurities in Rare-earth ions systems.	Quantum	Now
SI-MCh16	Enhancing Photon Extraction and Emission Rates. Low photon extraction efficiency and shortened coherence time and unstable charge state of NV− centres near the surface, affecting quantum sensing applications in Colour centres in wide-bandgap materials	Quantum	5 years
SI-MCh17	Micro and Nanofabrication Challenges e.g. precise positioning of Colour Centres for technologies based on colour-centre in diamond including purity control, defect characterisation, surface quality management, and functionalization for enhanced quantum sensing	Device	5 years
SI-MCh18	Challenges in fabrication methods and the need for large high-quality materials for practical deployment of 2D quantum platforms including monolayer fabrication, entanglement and superconductivity in SPEs, carrier recombination, and maintaining coherence in upscaled systems	Device	5 years
SI-MCh19	Technology challenges in quantum dots e.g. Single Electron Confinement	Technology	5 years
SI-MCh20	Establishing higher control over atom-array platform for better programmability of interactions and improved spin coherence in Ultracold atom arrays systems	Quantum	10 years
SI-MCh21	Achieving high brightness and purity in single-photon emitters (SPEs) at Room Temperature through control and tuning of properties, enhancing room-temperature functionality, and improving quantum efficiency	Quantum	5 years
SI-MCh22	Miniaturization of optical sources, detectors, and components, and quantum RF antennas	Device	10 years

SI-MCh23	Challenges with decoherence, short coherence times and dephasing by addressing hyperfine interactions, environmental impacts, and charge trap effects in various quantum systems	Quantum	5 years
SI-MCh24	Focus on exploring new materials and improving surface treatment techniques for enhancing frequency conversion, reducing noise in advanced materials, and overcoming limitations in conventional systems	Technology	Now
SI-MCh25	Cryogenic cooling system requirements for Superconducting Circuits	Environmental	5 years
SI-MCh26	Discovery of Non-Abelian Anyons	Quantum	10 years
SI-MCh27	Realization of Majorana Zero Modes in Hybrid Devices	Device	10 years
SI-MCh28	Integration of Topological States in Superconducting Devices	Device	10 years
SI-MCh29	Initialization, Control, and Readout of Individual Spins	Quantum	10 years
SI-MCh30	High-fidelity qubits	Quantum	5 years
SI-MCh31	Free-space optics problem	Technology	10 years
SI-MCh32	Utilization of diamond AFM tips for enhanced quantum sensing	Other	5 years
SI-MCh33	Atomic Vapor: Need for room temperature operation and precise rotation sensing	Other	10 years
SI-MCh34	Maccone-Ren technology concept	Technology	10 years
SI-MCh35	Ultrafast optical modulation for quantum applications	Other	5 years
SI-MCh36	Engineering of solid-state quantum systems for high performance	Quantum	5 years

Appendix 6: Full list of material developments for Sensing and Imaging

Material Developments	Impact	Feasibility
Ultra-low-loss optical materials for quantum photonic integrated circuits; Developing new materials for non-linear optics in quantum photonics	10	9
Development of materials towards on-chip photonic systems, e.g. integration of source/transmitter and receiver/detector	8	5
Quality control in defect materials e.g. SiC, Diamond, etc.; Tailoring doping, isotopic composition, purity, with resilient UK supply	5	7
Material quality and characterisation including trap density management, defect control, nano-atomic characterisation, and polycrystalline structure understanding	4	5
Advanced photonic material engineering including GaP metasurfaces, SPE integration, defect exploration in hBN and TMDs, and quantum emitter optimization for high-efficiency applications of single-photon emitters; Integration of quantum emitters with photonic networks for efficient coupling by silicon carbide for high-rate entangled states, employing micro/nanostructures in GaP for efficiency, applying defect and strain engineering in TMDs and hBN, and fabricating GaP metasurfaces for improved SHG efficiency; Efficient generation of quantum states of light by advancements in high-rate single photon and entangled photon sources, bound-state-in-continuum designs for conversion efficiency, GaP nanoantennae for ultrafast modulation, and compact SPDC sources using nonlinear metasurfaces; include layered materials (hBN, TMD) for photonic applications; ion beam additive manufacturing of crystalline nano-materials (with precursors)	4	4
Exploring alternative growth techniques like MBE and PEALD; research on materials with higher critical temperatures; High quality thin film materials	3	1
Establishing control over inter-molecular structured interactions (e.g. by synth-DNA conjugation)	3	5
Multifaceted material integration including heterojunctions, nanophotonic device fabrication, and precise interfacing techniques	2	3
Material discovery and formulation innovation	2	2
Rephrasing of #6 to: Existing material modification, incl. fabricating structures , maintaining photonic quantum structures (polarisation, etc.) OLD: Existing material modification, e.g. shape and size	2	2
Biexciton exploration, high-purity diamond synthesis, colour centre density enhancement, precision doping techniques, and surface optimization for improved quantum properties and coherence to address micro and nanofabrication challenges; Scaling up growth and processing of diamond of QT	2	3
Atomically precise material synthesis at scale	2	0
Automated discovery and characterisation of spin systems in different materials with optimal measurements	2	3
Device fabrication platform for EBL, Dry etching etc. like material beam etc. and National Epitaxy Facility; Expand nano-fab, e.g. flip chip lithography for hybrid devices	2	2
Advancements in quantum technology miniaturization of optics and devices, through cold atoms, single-ion logic, superconducting circuits, and atomic vapor optical measurements	1	0
Enhancing photon extraction and emission rates through advanced atomic species selection, cavity-enhanced laser phase noise filtering, integration into nanostructured hosts, and innovative fabrication techniques for quantum emitter integration	1	1
Spin system optimization, nano-diamond integration, graphene nanoribbon development, and advanced fabrication for quantum sensing and photonic application for enhancing frequency conversion, reducing noise in advanced materials, and overcoming limitations in conventional systems	1	0
Silicon-based quantum dots; ongoing research in semiconductor materials	1	3
Mid-IR SPEs and detectors	1	0

Appendix 7: Linking grid of challenges and material development areas for Sensing and Imaging

Material development / Challenge	Materials Development and Integration	Material Quality and Characterisation Quality Control	Material Synthesis	Engineering Techniques and Process Optimisation	Material and Quantum Systems Discovery and Modelling	Device Fabrication
A - Electrical readout and manipulation of quantum states; controllable coupling of individual solid-state; Integration of quantum emitters with photonic networks for efficient coupling; building devices with tailored capabilities for specific sensing applications e.g. nano-nmr; high-yield assembly of molecular devices; design molecules for devices rather than devices around molecules (architecture)	(partially)					
B - Developing characterisation tools for quantum platforms e.g., calibration in vivo, internal strain, and environmental variables affecting sensor effectiveness; nanoscale spectroscopic characterisation at low temperature; in-situ materials characterisation interfaces, operation under vacuum						
C - Micro and Nanofabrication Challenges e.g. precise positioning of Colour Centres for technologies based on colour-centres in diamond including purity control, defect characterisation, surface quality management, and functionalization for enhanced quantum sensing	(partially)					
D - Sustainability - materials, processes, devices, operation; Consideration of energy and resource investment in tech development						
E - Integration of quantum materials into robust packaging for real-world systems; micro -& nano fab for all materials –precise						
F - Integration of quantum emitters with photonic networks for efficient coupling; on-chip QD based photonic sources desired QD state, high brightness site control						
G - Integration challenges (scalability/robustness). Inhomogeneity of poorly controlled/characterised materials/interfaces/devices						

H - Engaging and inspiring communication/outreach; Facilitate interaction for 'pull' from industry and end users (e.g., clinicians)						
I - Identifying and growing improved bulk crystals with reduced nuclear spin concentration and ultra-low rare-earth background impurities in Rare-earth ions systems. identifying and growing high-purity materials with controllable nuclear spin concentration and ultra-low background impurities						
J - Structure function prediction for spin-based quantum sensing						
K - Challenges with decoherence, short coherence times and dephasing by addressing hyperfine interactions, environmental impacts, and charge trap effects in various quantum systems						
L - Material quality challenges e.g., inhomogeneity of poorly controlled/characterised materials/interfaces/devices						
M - Optical routing in waveguides, active modulation and switching at blue and ultraviolet wavelengths in Trapped ions systems						
Challenges in fabrication methods and the need for large high-quality materials for practical deployment of 2D quantum platforms including monolayer fabrication, entanglement, and superconductivity in SPEs, carrier recombination, and maintaining coherence in upscaled systems	(partially)					
Miniaturization of optical sources, detectors, and components, and quantum RF antennas						

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